EFFECTS OF GREENHOUSE GAS EMISSIONS ON WORLD AGRICULTURE, FOOD CONSUMPTION, AND ECONOMIC WELFARE *

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Abstract. Because of many uncertainties, quantitative estimates of agriculturally related economic impacts of greenhouse gas emissions are often given low confidence. A major source of uncertainty is our inability to accurately project future changes in economic activity, emissions, and climate. This paper focuses on two issues. First, to what extent do variable projections of climate generate uncertainty in agriculturally related economic impacts? Second, to what extent do agriculturally related economic impacts of greenhouse gas emissions depend on economic conditions at the time of impacts? Results indicate that uncertainty due to variable projections of climate is fairly large for most of the economic effects evaluated in this analysis. Results also indicate that economic conditions at the time of impact influence the direction and size of as well as the confidence in the economic effects of identical projections of greenhouse gas impacts. The economic variable that behaves most consistently in this analysis is world crop production. Increases in mean global temperature, for example, cause world crop production to decrease on average under both 1990 and improved economic conditions and in both instances the confidence with respect to variable projections of climate is *medium* (e.g., 67%) or greater. In addition and as expected, CO_2 fertilization causes world crop production to increase on average under 1990 and improved economic conditions. These results suggest that crop production may be a fairly robust indicator of the potential impacts of greenhouse gas emissions. A somewhat unexpected finding is that improved economic conditions are not necessarily a panacea to potential greenhouse-gas-induced damages, particularly at the region level. In fact, in some regions, impacts of climate change or CO_2 fertilization that are beneficial under current economic conditions may be detrimental under improved economic conditions (relative to the new economic base). Australia plus New Zealand suffer from this effect in this analysis because under improved economic conditions they are assumed to obtain a relatively large share of income from agricultural exports. When the climate-change and CO_2-fertilization scenarios in this analysis are also included, agricultural exports from Australia plus New Zealand decline on average. The resultant declines in agricultural income in Australia plus New Zealand are too large to be completely offset by rising incomes in other sectors. This indicates that regions that rely on agricultural exports for relatively large shares of their income may be vulnerable not only to direct climate-induced agricultural damages, but also to positive impacts induced by greenhouse gas emissions elsewhere.

1. Introduction

Rising greenhouse gas emissions are likely to affect agriculture worldwide in the future both directly through the yield-enhancing impacts on crops of rising atmospheric concentrations of carbon dioxide ('CO_2 fertilization') and indirectly

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through global climate change (Reilly et al., 1996; Gitay et al., 2001). Although the global scale of these phenomena and the increasing interconnectedness induced by economic globalization suggest that agricultural analyses require a global modeling framework, such analyses are rare and those that do exist have major limitations. Most global analyses, for example, combine yield changes from crop growth models with international economic models to estimate agricultural impacts of climate change or CO_2 fertilization (Kane et al., 1991; Rosenzweig et al., 1993; Reilly and Hohmann, 1993; Rosenzweig and Parry, 1994; Tsigas et al., 1997; Parry et al., 1999). Major drawbacks of this approach are that each farm-level adaptation (e.g., switching crop variety, changing planting or harvesting dates, etc.) has to be identified and assessed separately and potential climate-induced increases in production possibilities in areas currently not suitable for agricultural production are ignored.

Global analyses that incorporate the analogous region concept (e.g., that similar climates mean similar production practices) into international economic models avoid these limitations by implicitly capturing changes in crop or livestock outputs, production inputs, or management practices that farmers are likely to adopt under new climatic conditions (Darwin et al., 1994, 1995; Darwin, 1999). The major limitations of these analyses are that they have estimated the impacts of only relatively large increases in mean global temperature (2.8 to 5.2 °C) imposed on 1990 economic conditions. Similarly, they have estimated the direct benefits of only relatively large increases in atmospheric concentrations of CO_2, e.g., 225 parts per million by volume (ppmv), imposed on 1990 economic conditions (Darwin and Kennedy, 2000).

Despite these shortcomings, this research supports a number of generalizations. First, increases in mean global temperature ranging from 2.8 to 5.2 °C are likely to reduce world agricultural production and food security (Rosenzweig and Parry, 1994) or economic welfare (Darwin, 1999). There is less agreement on the impacts of smaller increases in mean global temperature. Parry et al. (1999) estimates that cereal production would fall (and prices rise) even at increases in temperature projected for 2020 or 2050.* Another recent global analysis, however, found that land suitable for agriculture would increase if mean global temperature were to rise uniformly by 1 to 3 °C even without increases in precipitation (Fischer et al., 2001). Parry et al.'s modeling framework does not simulate increases in the availability of land suitable for agriculture.

The second major finding is that costs and benefits of global climate change are not equally distributed around the world. Agricultural production and food security are likely to increase at higher latitudes and in alpine areas where temperatures are relatively cool, but are likely to decrease in tropical areas where temperatures are relatively warm or in dry areas where precipitation is relatively low (Rosenzweig

* Parry et al. did not report the increases in temperature simulated in their analysis. I am assuming that at least some are less than 2.8 °C because 2020 and 2050 are not too far into the future.

and Parry, 1994; Darwin et al., 1995; Parry et al., 1999). Changes in economic welfare follow a similar pattern (Darwin, 1999). This is also consistent with the finding that, although land suitable for agriculture would increase if mean global temperature were to rise uniformly, it would decrease in developing countries (Fischer et al., 2001).

A third finding is that the benefits of CO_2 fertilization are likely to offset at least some of any potential welfare losses generated by climate change (Rosenzweig et al., 1993; Reilly and Hohmann, 1993; Rosenzweig and Parry, 1994; Tsigas et al., 1997; Darwin and Kennedy, 2000). When measured by percent changes, economic benefits of CO_2 fertilization are generally larger in regions where agriculture is a relatively large component of the total economy. Benefits are generally smaller in regions that rely heavily on agricultural exports as a source of income (Darwin and Kennedy, 2000).

Many uncertainties, however, remain and quantitative estimates of the agriculturally related economic impacts of greenhouse gas emissions are given low confidence (Gitay et al., 2001). A major source of uncertainty resides in our inability to accurately project future changes in economic activity, emissions, and climate (Jones, 2000; Nakicenovic and Swart, 2000; Visser et al., 2000). Especially important to estimating the economic effects of the agricultural impacts of greenhouse gas emissions are projections of regional differences in climatic impacts, technological changes in agriculture, the availability of water resources, trends in food demand, and the wide array of possible adaptations (Parry et al., 1999). Although this source of uncertainty will always exist, the development of ways to quantify and categorize its impacts on estimates of economic activity will increase our ability to cope with it.

Another source of uncertainty originates in how agronomic impacts of greenhouse gas emissions are incorporated into economic models. Estimating the economic benefits of CO_2 fertilization, also listed in Parry et al. (1999), offers an example. Some early studies of greenhouse gas emissions assumed that percent changes in crop supply are equivalent to percent changes in crop yields. This assumption is not valid, however, because it confounds changes in supply with changes in quantity supplied. This error leads to an overestimation of the economic benefits of CO_2 fertilization by 61 to 166% (Darwin and Kennedy, 2000). A related source of uncertainty at present is our inability to simulate all of the effects of greenhouse gas emissions simultaneously. Reducing these sources of uncertainty involves devising or improving ways of simulating agronomic impacts in economic models. In this paper, I focus on uncertainty due to our inability to accurately project future changes in climate or economic activity.

2. Procedures

The procedures outlined in this section are designed to help answer two general questions. First, to what extent does the variability of GCM-based projections of climate generate uncertainty in agriculturally related economic impacts? Second, to what extent do agriculturally related economic effects of greenhouse gas emissions depend on economic conditions at the time of impact? To answer these questions I first estimate the economic impacts of various climate-change and CO_2-fertilization scenarios relative to economic conditions in 1990 and hypothetical projections of improved economic conditions. Next I quantify the economic variability (with respect to 1990 and improved economic conditions) associated with the climate-change scenarios. Then I compare the economic effects of imposing the climate-change scenarios on projections of improved economic conditions with the economic effects based on 1990 economic conditions. Finally, I compare the estimated benefits of CO_2 fertilization based on 1990 economic conditions with estimated benefits based on improved economic conditions.

2.1. SCENARIO DESCRIPTIONS

This analysis uses scenarios of climate change, CO_2 fertilization, and alternative economic conditions, which in this research are improved relative to 1990. The scenarios are for analytical purposes only. They are not predictions. They provide the basis for simulating climate change, CO_2 fertilization, and alternative economic conditions in a global modeling framework.

2.1.1. *Climate Change*

Projected changes in temperature and precipitation (see Table I) are developed from climatic conditions projected by eight general circulation models (GCMs). Increases in mean global temperature range from 1.0 to 5.2 °C. This is somewhat lower than the 1.4 to 5.8 °C range most recently projected by the Intergovernmental Panel of Climate Change (IPCC) for the end of the 21st century (Albritton et al., 2001). Increases in precipitation range from 1.3 to 15%. Four scenarios are from runs of equilibrium conditions generated by a doubling of greenhouse gas emissions. These runs were conducted with models at Oregon State University (OSU), the Geophysical Fluid Dynamics Laboratory's (GFDL), the Goddard Institute for Space Studies (GISS), and the United Kingdom Meteorological Office (UKMO). These $2 \times CO_2$ scenarios project mean global temperature to increase by 2.8 to 5.2 °C.

Three scenarios are based on results from transient climate change experiments performed with coupled ocean-atmosphere GCMs: the Hadley Centre's (HC) HadCM2 model (Viner and Hulme, 1997), the GFDL's GFDL89 model (Manabe et al., 1991; Manabe, Spelman, and Stouffer, 1992), and the Max Planck Institute's (MPI) ECHAM1-A model (Cubasch et al., 1992). Monthly temperature and precipitation estimates from the HC control and transient experiment (e.g., HadCM2SUL) for the 15-year period from 2041 to 2055 were obtained directly from the Climate Research Unit, University of East Anglia. The HadCM2SUL scenario assumes a one-percent per year increase in greenhouse gas concentra-

Table I
Projected changes in mean global temperature and precipitation

General circulation model	Year when calculated	Temperature change (°C)	Precipitation (%)
University of Illinois at Urbana-Champaign [a]	1996–1997	1.0	1.3
Max Planck Institute [b]	1990–1991	1.1	2.1
Geophysical Fluid Dynamics Laboratory [c]	1989	1.3	2.8
Hadley Centre [d]	1995	1.8	2.5
Oregon State University [e]	1985	2.8	8
Geophysical Fluid Dynamics Laboratory [f]	1988	4.0	8
Goddard Institute for Space Studies [g]	1982	4.2	11
United Kingdom Meteorological Office [h]	1986	5.2	15

[a] Schlesinger et al. (1997, 2000).
[b] Cubasch et al. (1992) and Greco et al. (1994).
[c] Manabe et al. (1991, 1992) and Greco et al. (1994).
[d] Johns et al. (1997).
[e] Schlesinger and Zhao (1989).
[f] Manabe and Wetherald (1987).
[g] Hansen et al. (1988).
[h] Wilson and Mitchell (1987).

tions. This yields a greenhouse gas concentration about 10% larger (e.g., 600 ppmv instead of 550 ppmv CO_2 equivalents) than that assumed by the Intergovernmental Panel on Climate Change (IPCC) business-as-usual IS92a emissions scenario in 2050 (IPCC, 1996). The scenario also assumes an increase in sulfate aerosol concentrations consistent with the IS92a scenario. Average monthly temperature and precipitation for the control and transient scenarios were calculated for the 2041–2050 period.

Average monthly temperature and precipitation from the GFDL and MPI GCMs were obtained from Greco et al. (1994). Values for 2050 were derived from selected 10-year periods of the transient experiments in which global mean surface air temperature was assumed to increase by 1.2 °C relative to 1990. This temperature change was estimated to be consistent with IS92a emissions (including cooling emissions like sulfates as well as greenhouse gases) and a temperature sensitivity of 2.5 °C (Wigley, Holt, and Raper, 1991). The first decade of the transient run was used as the control run because global average temperatures in the first decade of the two runs are nearly identical (Greco et al., 1994).

Another scenario is derived by interpolating equilibrium results for $2 \times CO_2$ and sulfates, e.g., $10 \times SO_4$, from the University of Illinois at Urbana-Champaign's (UIUC) AGC/MLO model to estimated changes in global mean surface air temperature for 2050 from the UIUC's EBC/UDO model (Schlesinger et al., 1997 and 2000). Assuming IS92a emissions and a temperature sensitivity of 2.5 °C, the projected change in temperature for 2050 is 0.96 °C = 1.28 – 0.32 °C, where 1.28 °C is the greenhouse gas component and –0.32 °C is the sulfate aerosol component. Data on monthly temperature and precipitation data for the control, equilibrium $2 \times CO_2$, and equilibrium $10 \times SO_4$ runs, and on global mean surface air temperature for 2050 were obtained directly from the Climate Research Group, Department of Atmospheric Sciences, UIUC. Average monthly temperature and precipitation for the control and equilibrium experiments were calculated from the last ten years of the simulations.

Precipitation does not increase monotonically with temperature. Nevertheless, the relationship between temperature and precipitation is proportionate at a constant level on average over the range of temperatures analyzed. In alternative regression models, parameters on squared increases in temperature and on temperature increases from 2.8 to 5.2 °C are not statistically significant at the 5% level (Table II). The positive correlation of precipitation with temperature is also supported by the fact that the estimates of the lower 95% confidence limit are always positive (Figure 1a). The interval between estimated 95% confidence limits is also relatively broad, e.g., ±2.2 and ±5.8% from trend for increases in mean global temperature of 1.0 and 5.2 °C, respectively, which suggests that precipitation results from GCMs are fairly variable.

Mean monthly changes in temperature and precipitation are interpolated to 0.5° grids and applied to observed mean monthly temperature and precipitation (Leemans and Cramer, 1991). Regional changes in temperature and precipitation can be calculated with these adjusted data (Tables III and IV). Mean temperatures increase over all land and in all regions (Table III). Temperatures over land increase monotonically with mean global temperatures, but regional temperatures may not. The range across regions for a given GCM is 0.8 °C for the UIUC scenario and 4.5 °C for the UKMO scenario, increasing on average as mean global temperature increases.

Like mean temperature, mean precipitation also increases over all land (Table IV). Regional precipitation, however, sometimes decreases. It only increases in all GCM scenarios in 25% of the regions. The range across regions for a given GCM is 12.3% for the GFDL89 scenario and 32.2% for the UKMO scenario, increasing on average as mean global temperature increases. Variability is also indicated by the fact that the estimates of the lower 95% confidence limit of the relationship between changes in temperature and precipitation over land are always

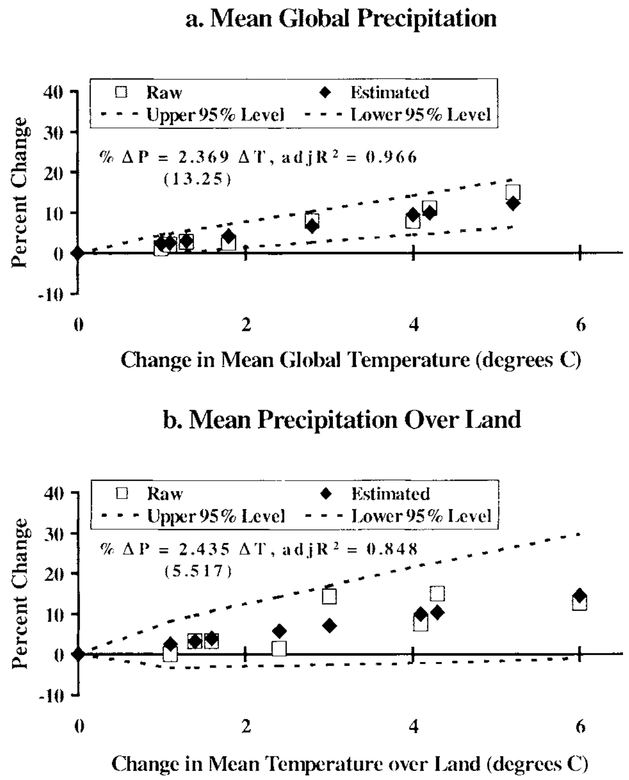

Figure 1. Estimated impacts of mean increases in temperature on mean changes in precipitation. Equations give parameter estimates (with student t-statistics in parentheses) of regression models based on projections from general circulation models.

negative (Figure 1b). In addition, the distance between estimated 95% confidence limits is broad, e.g., ±5.7 and ±15.4% from trend for increases in mean global temperature of 1.1 and 6.0 °C, respectively.

2.1.2. *CO_2 Fertilization*

There is only one CO_2 fertilization scenario. It is based on a 150-ppmv increase in atmospheric CO_2 from 1990 levels. The yield increases expected from this increase in atmospheric CO_2 are as follows: maize, sorghum, millet, and sugar cane, 4.7%; wheat, 14.7%; rice, 12.7%; soybeans, 22.7%; other crops, 16.7%. They are linearly interpolated from yield increases estimated for a 225-ppmv increase from 330 ppmv of atmospheric CO_2 (Rosenzweig et al., 1993). These yield increases are based on a worldwide crop modeling study that considers temperature, precipitation, irrigation, and mineral fertilization in combination with CO_2 fertilization (Rosenzweig and Iglesias, 1994). The CO_2 fertilization scenario does not increase yields of permanent pasture.

Table II
Effects of increases in mean temperature on mean percent increases in precipitation[a]

Area covered/ model	Change in temperature	Change in temperature squared	Change in temperature 2.8 to 5.2 °C	Adjusted R-squared[b]	Degrees of freedom	Average standard error
Global						
Model 1	2.369*** (13.253)			0.966	7	1.555
Model 2	1.467* (2.758)	0.255 (2.044)		0.979	6	1.230
Model 3	1.673** (3.582)		0.920 (1.874)	0.978	6	1.248
Over land						
Model 1	2.435*** (5.517)			0.848	7	3.839
Model 2	2.057 (1.125)	0.098 (0.229)		0.815	6	4.229
Model 3	1.308 (1.186)		1.549 (1.314)	0.856	6	3.736

[a] Parentheses indicate t-statistics. One, two, and three asterisks (*, **, ***) indicate statistical significance at the 5, 1, and 0.1% levels, respectively.
[b] Because the models lack intercept terms, the calculation of the coefficient of multiple determination, R^2, is $R^2 = 1 - \hat{e}'\hat{e}\boldsymbol{y}'\boldsymbol{y}$, where $\hat{e}$ is a vector of estimated errors and $\boldsymbol{y}$ is a vector of dependent variables. The adjusted $R^2 = 1 - (\hat{e}'\hat{e}/n - k)/(\boldsymbol{y}'\boldsymbol{y}/(n-1))$, where n is the total number of observations and k is the number of independent variables.

2.1.3. *Improved Economic Conditions*

Likewise, there is only one scenario of alternative economic conditions. It is derived from hypothetical projections of population, gross domestic product (GDP), per-capita food consumption, and technological advance in agriculture to 2050 assuming no change in climate (Tables V and VI). Growth rates for population and GDP were derived from projections used to generate the six emission scenarios prepared for the 1992 Intergovernmental Panel on Climate Change Supplementary Report (Greco et al., 1994). These projections are optimistic. They are most similar to assumptions underlying the 'A1' story line of rapid economic growth in the IPCC's Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000).

Projections of per-capita food consumption embody three basic assumptions. First, most of the increases in GDP are associated with increased household consumption of services and manufactured goods rather than with increased con-

Table III
Projected changes in mean annual surface temperature (°C), by region

Region	General circulation model [a]							
	UIUC	MPI	GFDL89	HC	OSU	GFDL88	GISS	UKMO
All Land [b]	1.1	1.4	1.6	2.4	3.0	4.1	4.3	6.0
United States	1.1	1.8	1.6	2.3	3.2	4.4	4.6	6.7
Canada	1.0	1.1	1.5	2.8	3.4	5.5	4.9	7.9
European Community	1.1	1.4	1.7	1.8	2.9	4.4	3.9	6.0
Japan	0.6	0.9	1.4	1.1	2.8	4.0	3.1	4.9
Other East Asia	1.0	1.4	2.0	1.7	2.8	4.1	4.2	6.1
Southeast Asia	0.8	1.0	1.1	2.1	2.1	2.4	3.7	3.4
Australia plus New Zealand	0.9	1.6	1.4	2.5	2.8	3.9	4.3	5.6
Rest-of-World	1.2	1.5	1.6	2.5	3.1	4.0	4.3	5.9
Former Soviet Union	1.2	1.4	2.0	2.7	3.6	5.2	4.8	7.6
Eastern, Northern Europe	1.4	1.2	1.9	2.3	3.6	5.7	4.3	6.5
Western, Southern Asia	1.1	1.6	1.5	1.9	3.2	3.5	3.8	5.3
Latin America	1.1	1.2	1.3	2.4	2.6	3.1	4.2	4.7
Africa	1.2	1.7	1.5	2.6	2.8	3.5	4.2	5.4

[a] The general circulation models are from the University of Illinois at Urbana-Champaign (UIUC), the Max Planck Institute (MPI), the Geophysical Fluid Dynamics Laboratory (GFDL), the Hadley Centre (HC), Oregon State University (OSU), Goddard Institute for Space Studies (GISS), and the United Kingdom Meteorological Office (UKMO).
[b] Except Antarctica.

sumption of agricultural commodities, processed foods, or raw materials. Second, increases in household consumption of all food-related commodities are assumed to be larger in developing countries than in developed countries. Third, in developing regions, increases in household consumption of livestock-related products, non-grain products, and other processed foods are assumed to be larger than increases in raw grains.

Technological advance in agriculture is expressed in terms of total factor productivity (TFP) in crop production (Table VI). Total factor productivity is the ratio of total outputs to total inputs. A rising TFP means that more outputs can be obtained from a given level of inputs. In this analysis agricultural TFP is assumed to rise faster in developing regions than in developed regions. This is consistent with the notion that regions particularly far behind have the most to gain from the diffusion of technology and hence may grow most rapidly (Gerschenkron, 1952). The worldwide average is about 0.70% per year over the 1990–2050 period. These are conservative projections. From 1973 to 1993, growth in agricultural TFP for

Table IV
Projected changes in mean annual precipitation (°C), by region

Region	General circulation model [a]							
	UIUC	MPI	GFDL89	HC	OSU	GFDL88	GISS	UKMO
All Land [b]	0.2	3.4	3.4	1.5	14.2	7.6	15.1	12.8
United States	5.0	–1.4	10.6	7.6	5.2	5.0	6.3	13.8
Canada	5.1	3.4	11.9	15.1	10.6	14.6	17.5	32.2
European Community	–1.3	–4.2	–0.4	1.8	4.6	5.3	6.5	10.0
Japan	–0.5	1.0	9.8	0.0	8.5	11.6	1.6	0.0
Other East Asia	–4.4	7.4	8.4	0.1	14.3	12.0	9.7	15.3
Southeast Asia	1.6	1.6	2.5	0.2	3.7	2.5	11.0	4.3
Australia plus New Zealand	8.3	–10.9	1.2	–7.8	23.3	–1.4	19.0	16.2
Rest-of-World	–0.7	4.7	2.0	0.8	16.5	7.4	16.9	11.4
Former Soviet Union	0.2	8.2	9.6	9.3	9.9	13.6	20.4	27.4
Eastern, Northern Europe	6.8	3.5	3.0	4.9	15.4	18.4	19.9	27.4
Western, Southern Asia	1.1	6.2	1.2	–9.6	11.0	12.8	11.9	11.3
Latin America	–0.4	5.7	0.9	0.6	22.8	5.1	14.6	6.0
Africa	–3.2	1.2	0.9	2.9	19.3	1.1	19.4	8.6

[a] The general circulation models are from the University of Illinois at Urbana-Champaign (UIUC), the Max Planck Institute (MPI), the Geophysical Fluid Dynamics Laboratory (GFDL), the Hadley Centre (HC), Oregon State University (OSU), Goddard Institute for Space Studies (GISS), and the United Kingdom Meteorological Office (UKMO).
[b] Except Antarctica.

the U.S. and nations in the European Union ranged from 1.6 to 2.3% per year (see data in Ball et al., 2001).

2.2. WORLD MODEL

All economic impacts in this analysis are estimated with the Future Agricultural Resources Model (FARM). FARM was developed by the Economic Research Service of the U.S. Department of Agriculture specifically to conduct research on global climate and other changes (Darwin et al., 1994, 1995, 1996; Darwin, 1999; Lewandrowski et al., 1999; Darwin and Kennedy, 2000; Darwin and Tol, 2001). It is composed of two components – an environmental framework and an economic framework (Figure 2).

Table V

Average annual growth rates (%) of population, gross domestic product, and per-capita food consumption for a scenario depicting improved economic conditions

Region	Population	Gross domestic product	Per-capita food consumption
United States	0.3	2.1	0.14
Canada	0.9	2.7	0.14
European Community	0.1	1.9	0.12
Japan	–0.1	1.8	0.12
Other East Asia	0.7	3.2	0.87
Southeast Asia	1.0	3.8	0.90
Australia plus New Zealand	0.7	2.6	0.13
Rest-of-World	1.4	3.2	0.57
Total	1.1	2.4	0.70

Table VI

Average annual growth rates (%) of total factor productivity for the reference scenario with improved economic conditions

Crop	Developed regions 1990–2050	Developing regions 1990–2050
Wheat, rice, and maize	0.40	1.60
Other grains	0.16	0.64
Potatoes	0.20	0.80
Other roots and tubers	0.16	0.64
Pulses	0.10	0.40
Soybeans	0.19	0.76
Other crops	0.12	0.48

2.2.1. *Environmental Framework*

FARM's Environmental Framework consists of a geographic information system with a 0.5° resolution. It links climate variables with six land classes (LC) in twelve regions – the United States, Canada, the European Community (as of 1990), Japan, other East Asia (South Korea and China, including Taiwan and Hong Kong), Southeast Asia (Indonesia, Malaysia, Philippines, Singapore, and Thailand), Australia

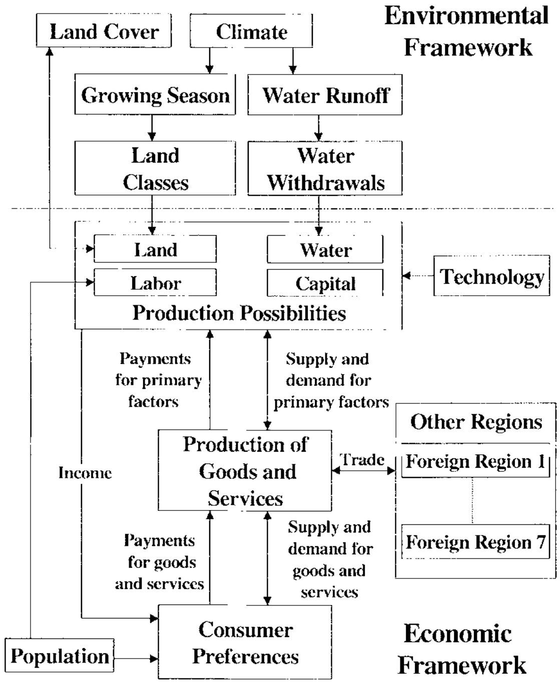

Figure 2. FARM modeling framework.

plus New Zealand, the former Soviet Union plus Mongolia, eastern and northern Europe plus Greenland, western and southern Asia, Latin America, and Africa.

Land classes are defined by length of growing season – the length of time during the year that soil temperature and soil moisture conditions are continuously suitable to crop growth (Figure 3). Hence, LCs are similar to what the Food and Agriculture Organization of the United Nations calls 'agro-ecological zones' (Food and Agriculture Organization of the United Nations, 1996). Length of growing season is calculated from observed mean monthly temperature and precipitation using a soil temperature and moisture algorithm (Leemans and Cramer, 1991; Eswaran et al., 1995.

Land-class boundaries generally reflect thresholds in crop production possibilities. Crop production in LC1 and rain-fed LC2 is marginal and restricted to areas where growing seasons approach 100 days. LC1 and LC2 (without irrigation) are limited to one crop per year. Principal crops on LC3 are wheat and other short-season crops. LC3, too, is limited to one crop per year. The growing season on LC4 is long enough to produce maize as well as allow for some double cropping. Major crops on LC5 are millet, sorghum, tobacco, cotton and rice; double cropping is common. Year-round growing seasons characterize LC6, which enables it to provide tropical fruits, sugar cane, cocoa bean, and coffee. The framework tracks 33 crop categories by LC and region in all. They are wheat, other cool season

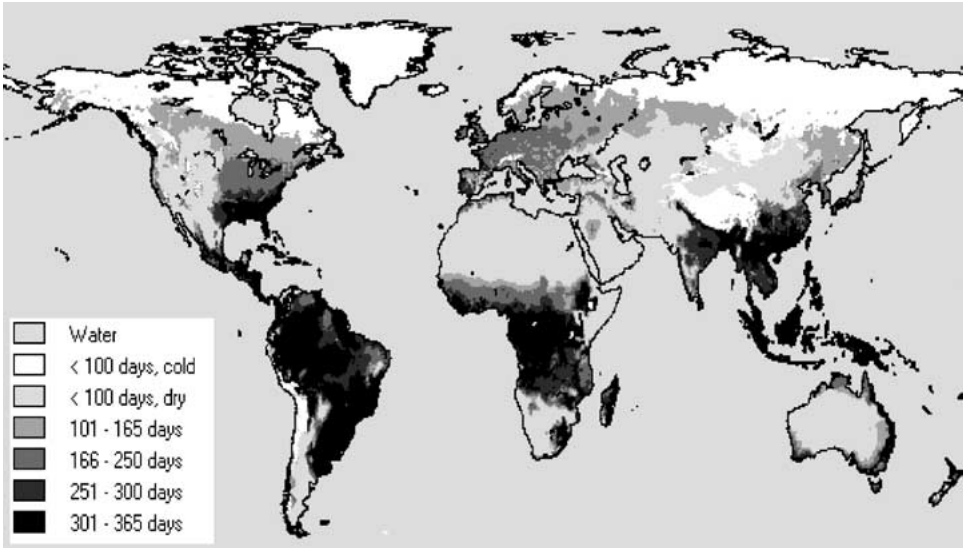

Figure 3. Land classes (LC) under initial climatic conditions. LC1 occurs primarily in polar and alpine areas, while LC2 represents mainly semi-desert and desert areas. LC3 is located primarily in northern latitudes. LC4 is located throughout temperate and tropical areas. LC5 is located in lower latitudes and equatorial areas. LC6 is mostly located in tropical areas.

grains, paddy rice, maize, millet, sorghum, potatoes, other roots and tubers, pulses, soybeans, cool season oils, warm season oils, tropical oils, cool season vegetables, warm season vegetables, other vegetables, dates, berries, cool season fruit, warm season fruit, tropical fruit, sugar beets, sugar cane, hops, tobacco leaves, cotton, cool season fibers, tropical fibers, treenuts, coffee, cacao beans, tea, and rubber.

The distribution of cropland across LCs varies by region. In developed regions (e.g., United States, Canada, Europe, Japan, Australia, New Zealand, and the former Soviet Union), most cropland occurs on LC2–LC4. In developing regions (e.g., Africa, Latin America, and all Asia except Japan), most cropland occurs on LC2, LC5, and LC6 (Figure 4). A particular crop may be grown on one or more land classes. Maize, for example, is grown on LC4 through LC6, as well as on LC2 or LC3 where irrigation provides LC4- through LC6-like growing conditions.

2.2.2. *Economic Framework*

FARM's Economic Framework consists of a computable general equilibrium (CGE) economic model that provides comprehensive measures of worldwide economic activity. It is an aggregation and extension of the Global Trade Analysis Project's (GTAP) 1990 model of economic activity (Hertel, 1993, 1997). The CGE economic model divides the world into eight geographic regions – the United States, Canada, the European Community, Japan, other East Asia, Southeast Asia, Australia plus New Zealand, and the Rest-of-World (e.g., the former Soviet Union plus Mongolia, eastern and northern Europe plus Greenland, western and

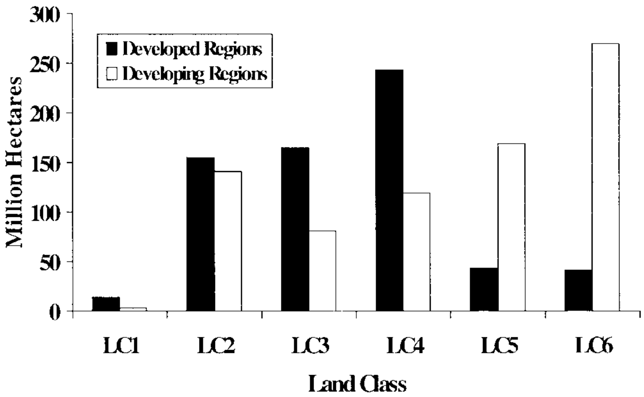

Figure 4. Distribution of cropland by land class in developed and developing regions. Developed regions include the United States, Canada, Europe, Japan, Australia, New Zealand, and the former Soviet Union. Developing regions include Africa, Latin America, and all Asia except Japan.

southern Asia, Latin America, and Africa). The high level of aggregation in the Rest-of-World region reflects the limitations of the 1990 GTAP model.

In addition to an economic sector that produces region-specific capital, each region has 11 economic sectors that produce 13 tradable commodities (Table VII). The agricultural sectors are crops and livestock. Crops sectors produce three tradable commodities – wheat, other grains, and non-grains. Other grains and non-grains are aggregates of the crop categories tracked in the Environmental Framework. Livestock sectors produce one tradable commodity. Other sectors that produce one commodity are (1) forest products, (2) coal, oil, and gas, (3) other minerals, (4) fish, meat, and milk, (5) other processed foods, (6) textiles, clothing, and footwear, (7) nonmetallic manufactures, (8) other manufactures, and (9) services. Each crops, livestock, and forestry sector in a region is divided in up to six subsectors – one for each LC. Each LC and region combination produces a unique set of crop, livestock, and forestry products by combining the traded commodities with primary factors of production (e.g., land, water, labor, and capital). Other sectors also utilize land from different LCs but their products are not differentiated by LC. All land is assigned to the production of some good or service.

Producers of the tradable commodities of a region are assumed to minimize production costs. A super household in each region is assumed to maximize the utility it obtains by consuming private goods and services, government services, and saving. Structural parameters in production and utility functions allow for adjustments in crop yields, TFP, or consumption patterns. Regions are linked through trade and financial flows. As a general equilibrium system, the CGE economic model accounts for all expenditure flows from households through domestic and international markets to producing sectors and then accounts for all income flows back to households, which are assumed to own all primary factors of production (e.g., water, land, labor, and capital).

Table VII
Regional, sectoral, and commodity aggregation for FARM

A.	*Regional aggregation*	*D.*	*Commodity aggregation*
1.	Australia plus New Zealand	1.	Wheat
		2.	Other grains
2.	Canada		Paddy rice
			Other grains
3.	United States of America	3.	Nongrains
		4.	Livestock
4.	Japan		Wool
			Other livestock products
5.	Other East Asia	5.	Forestry
	Republic of Korea	6.	Coal, oil, and gas
	People's Republic of China	7.	Other minerals
	Hong Kong	8.	Fish, meat, and milk
	Taiwan		Fishing
			Meat products
6.	Southeast Asia		Milk products
	Indonesia	9.	Other processed foods
	Malaysia		Processed rice
	Philippines		Other food products
	Thailand		Beverages and tobacco
		10.	Textiles, clothing, and footwear
7.	European Community		Textiles
			Wearing apparel
8.	Rest-of-World		Leather, fur, and their products
		11.	Other nonmetallic manufactures
			Lumber and wood products
B.	*Sectoral aggregation*		Pulp, paper, and printed products
1.	Crops (six sectors)		Petroleum and coal products
2.	Livestock (six sectors)		Chemicals, rubber, and plastic
3.	Forestry (six sectors)		Nonmetallic mineral products
4.	Coal, oil, and gas	12.	Other manufactures
5.	Other minerals		Primary iron and steel
6.	Fish, meat, and milk		Primary nonferrous metals
7.	Other processed food		Fabricated metal products
8.	Textiles, clothing, and footwear		Transport industries
9.	Other nonmetallic manufactures		Other manufacturing and equipment
10.	Other manufactures		Other manufacturing
11.	Services	13.	Services
12.	Fixed capital formation		Electricity, gas, and water
			Construction
C.	*Endowments*		Trade and transport
1–6.	Six land classes		Other services (private)
7.	Water		Other services (government)
8.	Labor		Other services (dwellings)
9.	Capital	14.	Fixed capital formation

The economic flows in FARM's CGE model reflect equilibrium economic conditions in 1990. Counter-factual conditions are simulated with exogenously imposed shocks on FARM's variables or parameters. These shocks induce a series of adjustments that end in a new equilibrium. Economic impacts of counter-factual conditions are represented by the differences between the initial and ending equilibria. This process is implemented and solved with GEMPACK software (Harrison and Pearson, 1996).

Basic indicators of agriculture's sensitivity to counter-factual conditions include changes in crop and livestock production and prices, per-capita food consumption and prices, and per-capita welfare. Percent changes in world crop production and prices are derived from Fisher quantity and price indices of world changes in wheat, other grains, and non-grains production.* World changes in wheat, other grains, and non-grains quantities and prices used to calculate these Fisher indices are quantity-weighted sums of regional changes. Percent changes in world production and prices of livestock are Fisher quantity and price indices of regional changes. Percent changes in world per-capita food consumption and prices are sums of regional percent changes weighted by population. Regional percent changes in food consumption and prices are in turn derived from Fisher quantity and price indices of wheat, other grains, non-grains, livestock, fish-meat-milk, and other processed foods consumed directly by households.

Percent changes in per-capita welfare, w, are derived from estimates of equivalent variation (EV) – the difference, in terms of money expenditure on consumption and saving at pre-change prices, between the level of consumer satisfaction with change and the level of consumer satisfaction without change. They are calculated as $w_i = 100 * \mathrm{EV}_i/\mathrm{TE}_i$, where TE_i is money expenditure on consumption and saving in region i prior to the change. Percent changes in world per-capita welfare are sums of regional percent changes weighted by population. This approach helps to avoid some of the problems associated with simply summing regional, dollar-delineated welfare measures. First, a simple sum of dollar values assumes income parity across regions. Income parity implies that the welfare generated by a dollar's expenditure in the U.S. is equal to the welfare generated by a dollar's expenditure in China despite the fact that a U.S. dollar buys more goods and services in China than in the U.S. Second, a simple sum does not account for regional differences in population; an impact that affects 250 million people is given the same weight as an impact that affects 1 billion people.

* Fisher price indices, P_F, are calculated as $P_F = (P_L * P_P)^{0.5}$, where P_L is a Laspeyres price index, e.g., $P_L = \Sigma Q_0 P_1 / \Sigma Q_0 P_0$, and P_P is a Paasche price index, e.g., $P_P = \Sigma Q_1 P_1 / \Sigma Q_1 P_0$, P and Q indicate price and quantity, respectively, and subscripts 0 and 1 represent initial and ending conditions, respectively. Fisher quantity indices, Q_F, are calculated as $Q_F = (Q_L * Q_P)^{0.5}$, where $Q_L = \Sigma Q_1 P_0 / \Sigma Q_0 P_0$ and $Q_P = \Sigma Q_1 P_1 / \Sigma Q_0 P_1$ (Fisher, 1922). Percent changes are calculated as $x_F = 100 * (X_F - 1)$, where x and X represent P or Q.

2.3. ECONOMIC SIMULATIONS

The scenarios described in Section 2.1 provide a number of counter-factual conditions that FARM can simulate. Climate change, for example, is simulated by redistributing land uses according to the new land-class patterns generated by the GCM projections. CO_2 fertilization is simulated by adjusting structural parameters in FARM's crop production functions. Improved economic conditions are simulated by increasing regional levels of labor and capital and adjusting structural parameters in FARM's food demand and crop production functions.

2.3.1. *Climate Change*

The initial impacts of climate change are simulated in FARM's Environmental Framework, which calculates the new land-class patterns associated with the changes in temperature and precipitation projected by the GCMs (see Section 2.1.1). In all climate-change scenarios, the area covered by LCs with longer growing seasons tends to increase at high latitudes, while the area covered by LCs with shorter growing seasons tends to increase in the tropics (Figure 5). The former is primarily due to increases in soil temperature; the latter is due to decreases in soil moisture. Land-class changes at mid latitudes are mixed. These patterns are particularly apparent on net changes of existing cropland (Figure 6). In developed regions, LC4 cropland decreases, while LC5 and LC6 cropland increase. The opposite occurs in developing regions. The magnitude of these shifts generally increases as global temperature increases.

The economic impacts of climate change are simulated by redistributing land use in FARM's Economic Framework to conform to the new land-class patterns generated by the GCM projections. This changes the production possibilities of all regions simultaneously and generates a host of responses by economic agents worldwide (see Figure 2). Crop producers adapt to the new climatic conditions by adjusting their production practices. Where LC3 changes to LC4, for example, producers add maize to their crop mix. Where LC4 changes to LC3, producers drop maize from their crop mix (except where irrigation provides LC4-like conditions). Additional economic adaptations include abandoning agriculture in areas where climate change reduces production possibilities and expanding or establishing agriculture in areas where climate change increases production possibilities. Hence, crops automatically migrate to areas where climatic conditions are suitable for their growth.

2.3.2. *CO_2 Fertilization*

Yield changes generated by CO_2 fertilization are applied to the 33 crop categories tracked in FARM's Environmental Framework (see Section 2.1.2 above). Then aggregate yield changes for wheat, other grains, non-grains, and total crops are calculated for all LC and region combinations in FARM's Economic Framework. The direct aggregate percent changes in yield induced by rising levels of atmospheric

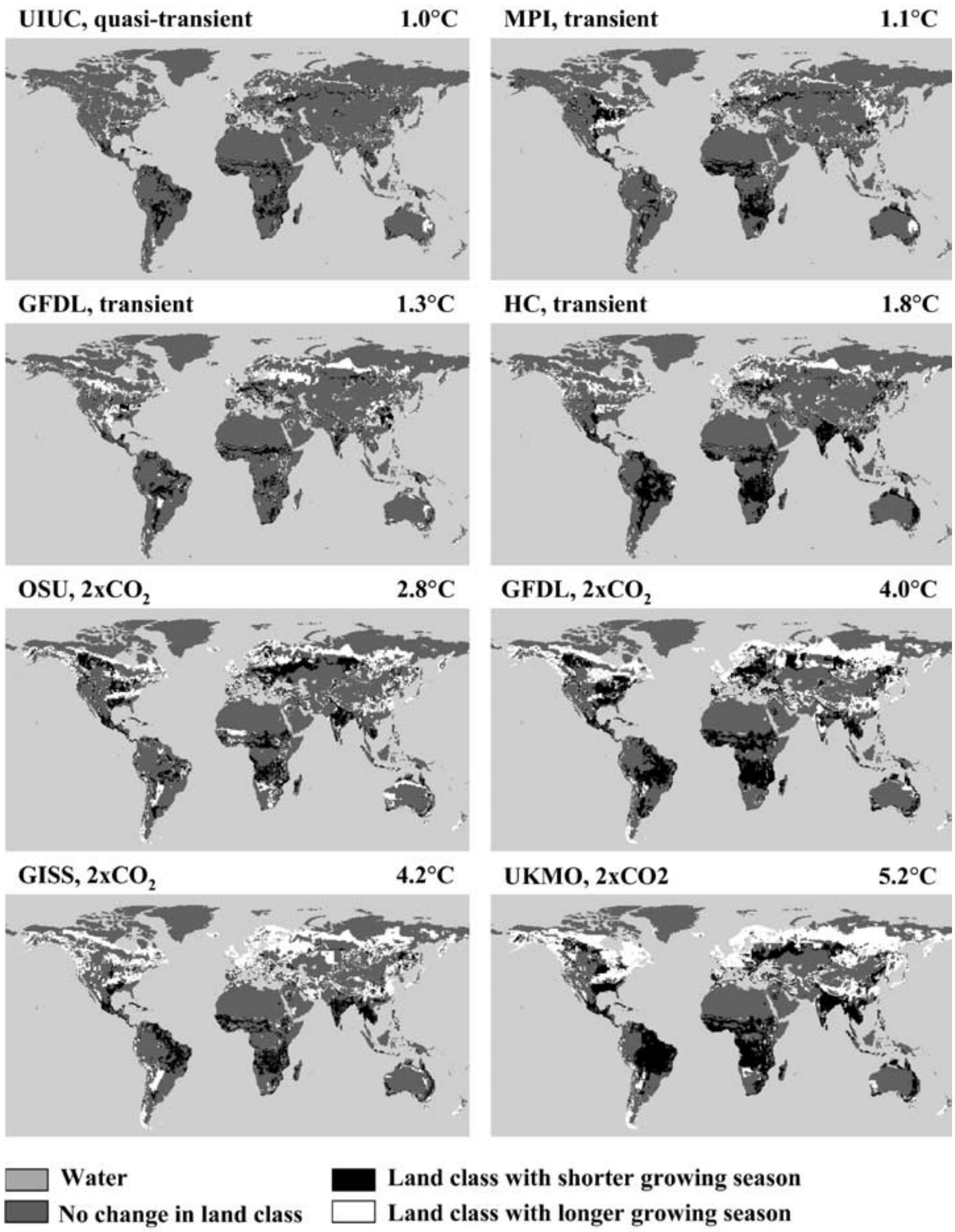

Figure 5. Estimated change in land class. Estimated at a resolution of 0.5° latitude and longitude.

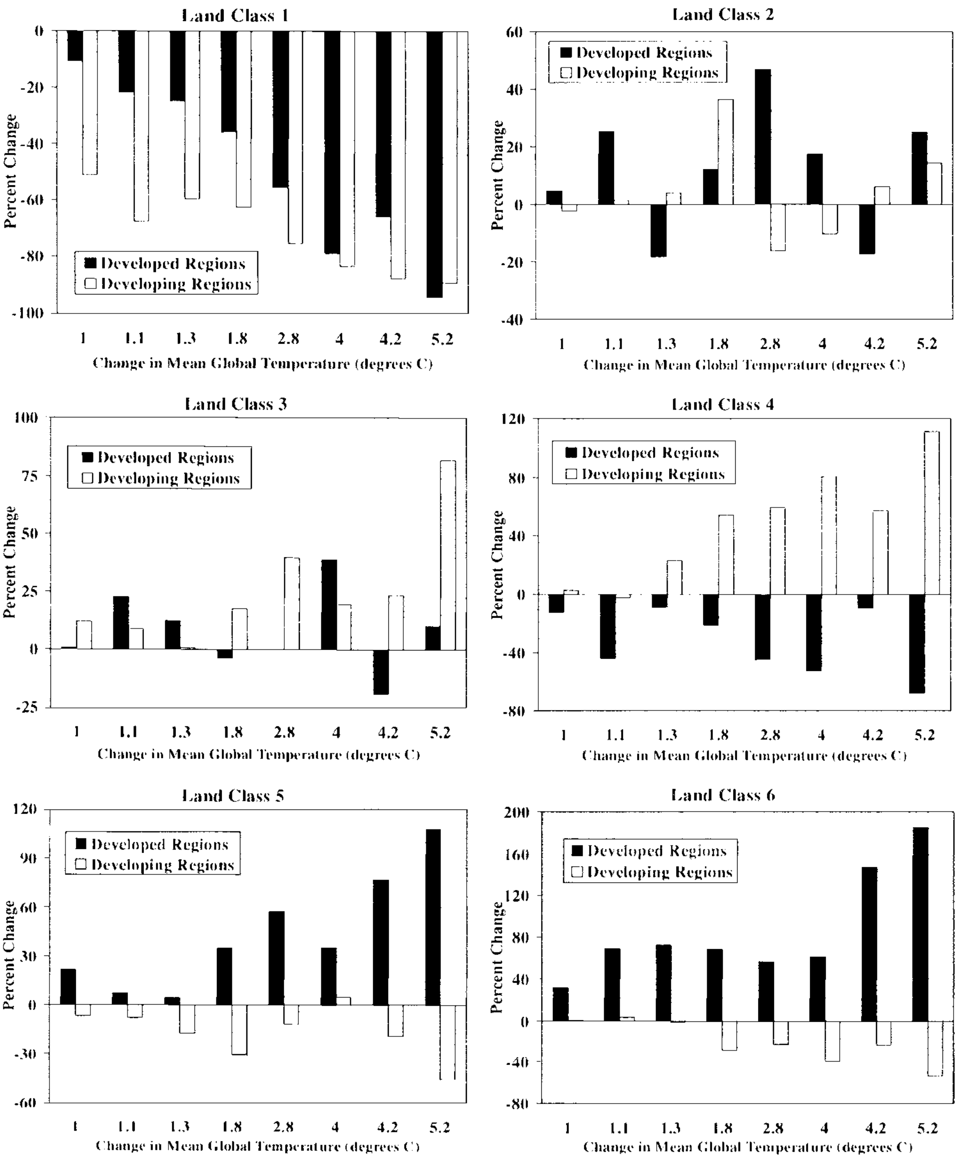

Figure 6. Estimated impacts of global climate change on land-class areas of existing cropland. Developed regions include the United States, Canada, Europe, Japan, Australia, New Zealand, and the former Soviet Union. Developing regions include Africa, Latin America, and all Asia except Japan.

CO_2 are implemented by adjusting structural parameters in FARM's crop production functions as land-, labor- and capital-saving technological changes (Darwin and Kennedy, 2000). Saving in land is equivalent to the percent change in yield. Savings in labor and capital are equivalent to one-half the percent change in yield. Other inputs are not adjusted. This approach avoids overestimating the economic benefits of the agronomic impacts of CO_2 fertilization outlined in the *Introduction*.

2.3.3. *Improved Economic Conditions*

Shocks for simulating improved economic conditions are developed in two steps. First, crop-specific changes in TFP (see Section 2.1.3 above) are applied to the 33 crop categories tracked in FARM's Environmental Framework to obtain aggregate TFPs for wheat, other grains, non-grains, and total crops for all LC and region combinations in FARM's Economic Framework. These aggregate increases in TFP are implemented by adjusting structural parameters in FARM's crop production functions as labor- and capital-saving technological changes, with greater savings attributable to labor than to capital. Hence, technological advance benefits all crops. There are, however, some constraints. Technologically induced changes in the length of a crop's growing season, for example, are implicitly confined within current land-class thresholds. Growing maize on rainfed LC3 cropland is precluded. Technological advance in agriculture also is assumed to be independent from CO_2 fertilization. Agronomists, for example, will not develop new crops that are able to concentrate CO_2 in their leaves above ambient levels.

Next, FARM's CGE economic model estimates the additional labor and capital required to obtain the higher levels of GDP, population, and per-capita consumption of food presented in Table V, given the changes in TFP. These estimated increases in labor and capital along with the increases in population and TFP then serve as the exogenous shocks for improved economic conditions (see Figure 2). These shocks are beneficial in all regions. Rates of growth in per-capita welfare are about 1.8% in developed regions, about 2.5% in the Other East Asia and Southeast Asia regions, and 1.8% in the Rest-of-World region. The world's average rate of growth in per-capita welfare is 2.0%.

2.4. ANALYTICAL METHODS

FARM's estimated changes in agricultural production, food consumption, and economic welfare are evaluated in three separate analyses. Economic uncertainty due to the variability of climatic projections is statistically quantified with linear regression models. I also use linear regression models to evaluate the effects of improved economic conditions on the impacts of climate change. The effects of improved economic conditions on the impacts of CO_2 fertilization are evaluated with a simple non-statistical comparison.

2.4.1. *Economic Uncertainty Due to Variable Projections of Climate*

I assess the economic uncertainty due to variable projections of climate by deriving 'summary functions' of FARM's estimated impacts of the climate changes generated by the eight GCMs discussed in Section 2.1.1 and imposed on 1990 economic conditions. These summary functions are obtained by regressing the FARM-based economic impacts on the GCM-based changes in mean global temperature. The functional form of the regression models is:

$$Y = \beta_0 T + \mu\,, \tag{1}$$

where Y is a vector of percent changes in some economic variable estimated by FARM, T is a vector of changes in mean global temperature, μ is a vector of errors, and β_0 is the parameter that indicates the relationship between changes in mean global temperature and economic impacts. The errors are assumed to be heteroskedastic, that is, variance$(\mu_i) = \sigma^2|T_i|$. This means that they become larger as the size of the change in temperature increases. Intercept terms are not included in the regression models. Hence, the summary functions implicitly include the origin, which simply means that temperature must change in order to generate an impact.⋆

The summary functions, in turn, provide additional estimates of economic impacts that are related solely to changes in mean global temperature. These 'summary estimates' indicate the extent to which FARM's estimates exhibit any general patterns or trends. Deviations from trends captured by the summary estimates are due to variations in climate input, e.g., differences in temperature and precipitation patterns generated by the various GCMs. The relative size of these deviations is obtained from 95% confidence limits, $L_{0.95,i}$, of the summary estimates of economic impacts associated with a given increase in mean global temperature, e.g.,

$$L_{(0.95,i)} = \hat{\boldsymbol{Y}}_i \pm t_{n-k,0.025)}\sigma_i[\boldsymbol{x}_i'(X'X)^{-1}\boldsymbol{x}_i + 1]^{0.5}, \tag{2}$$

where $\hat{\boldsymbol{Y}}_i$ is the summary estimate of an economic variable at temperature T_i, t is a t-statistic with $n - k$ degrees of freedom and a two-sided probability level of 5%, σ_i is the estimated standard error of the ith observation, $\boldsymbol{x}_i = T_i$ represents the temperature variable of the ith observation, and $X = T$ represents the vector of temperature variables for all the observations. These limits indicate where another set of economic impacts (estimated by FARM with climate input from one of the GCMs listed in Section 2.1.1) would fall with 95% probability.

Another feature of the confidence limits is that they indicate the extent to which FARM-based estimates are likely to be less than or greater than zero. If the 95% confidence interval of an estimate does not encompass zero, then new estimates are

⋆ Another set of regression models with quadratic temperature terms, e.g., $Y = \beta_0 T + \beta_1 T^2 + \mu$, also were developed to test for hill-shaped or U-shaped relationships between temperature and economic variables that were found in previous studies (Darwin, 1999; Mendelsohn and Schlesinger, 1999; Mendelsohn et al., 2000). The parameters on the quadratic temperature terms, β_1, are not, however, statistically significant, so these models are not presented here. They are available from the author upon request.

likely to be positive or negative with statistical significance at the 5% level. Similar confidence limits also can be estimated for two-sided probability levels of 67 and 33%, e.g.,

$$L_{(0.67,i)} = \hat{\boldsymbol{Y}}_i \pm t_{(n-k,0.165)}\sigma_i[\boldsymbol{x}_i'(X'X)^{-1}\boldsymbol{x}_i + 1]^{0.5} \tag{3a}$$

and

$$L_{(0.33,i)} = \hat{\boldsymbol{Y}} \pm t_{n-k,0.335)}\sigma_i[\boldsymbol{x}_i'(X'X)^{-1}\boldsymbol{x}_i + 1]^{0.5} \tag{3b}$$

by using an alternative t-statistic. These two sets of limits indicate where another set of FARM-based economic estimates would fall with, respectively, 67 and 33% probability. If these confidence intervals of an estimate do not encompass zero, then new estimates are likely to be positive or negative with statistical significance at the 33 and 67% levels, respectively. The 95, 67, and 33% confidence limits also correspond to levels recently used by the IPCC to categorize the confidence of conclusions as *very high*, *high*, and *medium*, respectively (IPCC, 2001). Confidence less than *medium* is *low*.

2.4.2. *Effects of Improved Economic Conditions on Climate Change Impacts*

Evaluating the effects of improved economic conditions on the impacts of climate change requires two steps. I first estimate the economic impacts of simultaneously imposing (1) the alternative land class patterns generated by the four GCMs that predicted the smallest increases in temperature (e.g., from 1.0 to 1.8 °C) and (2) the shocks that simulate improved economic conditions. The estimated economic impacts of climate change are derived by calculating percent changes relative to economic impacts from a simulation of just improved economic conditions. Next, I re-estimate the summary functions by including the new FARM-based estimates with improved economic conditions as observations. The functional form for the summary-function models is:

$$Y = \beta_0 T + \beta_1 TD + \mu\,, \tag{4}$$

where D is a (0,1) vector which equals 1 for economic impacts of new observations and equals 0 otherwise. The effect of improved economic conditions is indicated by the statistical significance of parameter β_1. If β_1 is statistically significant, then one can say that the improved economic conditions outlined in Section 2.1.3 modify the climate change impacts. Confidence limits for the summary-function estimates of impacts under improved economic conditions are also estimated for two-sided probability levels of 95, 67, and 33%. These indicate how improved economic conditions may affect the level of confidence associated with variable projections of climate.

2.4.3. *Effects of Improved Economic Conditions on the Impacts of CO_2 Fertilization*

Depicting the effects of improved economic conditions on the impacts of CO_2 fertilization is relatively straightforward. I first estimate the economic impacts of imposing the changes in yield induced by CO_2 fertilization (see Section 2.1.2) on 1990 economic conditions. Next, I estimate the economic impacts of imposing the CO_2-fertilization shocks simultaneously with the shocks that simulate improved economic conditions. The estimated economic impacts of CO_2 fertilization in the second case are derived by calculating percent changes relative to economic impacts from a simulation of just improved economic conditions. Estimated economic impacts from these two scenarios are presented in a table and simply (e.g., non-statistically) compared.

3. Findings

I confine my analysis to greenhouse-gas impacts on world crop and livestock production and prices, world per-capita food consumption and prices, and per-capita welfare both for the world and for eight geographic sub-regions. There are many results and it is easy to get distracted by specific observations that at first glance appear to be counterintuitive. To help alleviate such distractions, I checked the results for consistency with a basic economic story. The results of this check lead me to conclude that specific counterintuitive observations are attributable primarily to variations in climate projections and the way regions and agricultural commodities are aggregated in the model.

Here is the basic economic story. Imposing the alternative land-class patterns in the climate change scenarios or adjusting structural parameters in crop production functions in CO_2 fertilization scenarios shifts supplies of agricultural commodities (recall Figure 2). If the supply of an agricultural commodity increases as a result, then its production is expected to increase and its price to decrease (and vice versa). Correlation coefficients of –0.625* and –0.782** indicate that estimated climate-induced changes in world production and price of crop and livestock commodities, respectively, are in fact inversely related.⋆ World food consumption and price also move in opposite directions as indicated by a correlation coefficient of –0.970***.

The relationship between crop and livestock production is less certain. On the one hand, production of some livestock utilizes feed crops such as maize as inputs. On the other hand, livestock production is a substitute for crop production in areas where crop productivity is relatively low. This lack of certainty in the relationship between crop and livestock production is indicated by a correlation coefficient of –

⋆ One, two, and three asterisks (*, **, ***) indicate statistical significance at the 5, 1, and 0.1% levels, respectively, for 10 (e.g., 12–2) degrees of freedom. World impacts of CO_2 fertilization are obviously consistent with the economic story. Including them would increase statistical significance of all the correlation coefficients reported here.

0.082. World livestock production is, however, associated with world production of other grains, an important source of livestock feeds (not shown). Their correlation coefficient is 0.719**.

Because crops are major sources of food, increases or decreases in one are expected to lead to increases or decreases, respectively, in the other. This is confirmed by a correlation coefficient of 0.582* between crop production and food consumption. The relationship between livestock and food is less certain. Livestock production, for example, may increase in some instances because the ability to produce crops (and food) declines. This lack of certainty in the relationship between livestock production and food consumption is indicated by a correlation coefficient of 0.125. Finally, increases in the consumption of food are expected to generate increases in per-capita welfare. This is confirmed by a correlation coefficient of 0.895***.

3.1. ECONOMIC UNCERTAINTY DUE TO VARIABLE PROJECTIONS OF CLIMATE

FARM's estimated impacts of climate change imposed on 1990 economic conditions are presented in Table VIII. Variability is indicated by the fact that the impacts on each economic variable do not monotonically increase or decrease as mean global temperature increases. In addition, most economic variables incur both positive and negative impacts over the range of mean increases in temperature. More explicit details are presented during the analysis and discussion of this variability.

3.1.1. *Results*

The variability reflected in the individual observations is statistically summarized by trends and confidence limits. Trends provide information about the average size of the impacts attributable to increases in mean global temperature. Confidence limits provide information about the amount of variability due to differences in temperature and precipitation patterns. Confidence limits also indicate the level of confidence that an economic variable will increase or decrease as mean global temperature increases.

Summary functions derived by regressing FARM's estimates of economic impacts on the GCM-based increases in mean global temperature are presented in Table IX. The parameter estimates for changes in temperature indicate the percent change of impact generated by a 1 °C-increase in mean global temperature. Economic impacts exhibiting statistically significant (at the 5% level) downward trends with respect to increases in mean global temperature are world crop production, livestock production, food consumption, and per-capita welfare, as well as per-capita welfare in the European Community and Southeast Asia. Per-capita welfare in the Rest-of-World regions exhibits a downward trend statistically significant at the 10% level. Economic impacts exhibiting statistically significant (at the 5% level) upward trends with respect to increases in mean global temperature are the world crop price, world livestock prices, and per-capita welfare in Canada, Japan,

Table VIII
Estimated annual economic impacts (% change) of climate change [a]

Economic variable	Change in mean global temperature (°C)							
	1.0	1.1	1.3	1.8	2.8	4.0	4.2	5.2
World								
Crop production [b]	–0.28	–0.38	–0.47	–0.83	–0.53	–0.50	–0.51	–1.27
Livestock production [c]	–0.05	–0.16	–0.03	–0.03	–0.26	–0.34	–0.29	–0.49
Food consumption [d]	–0.01	–0.04	–0.04	–0.09	–0.05	–0.03	0.03	–0.22
Crop price [b]	0.23	1.10	0.59	1.53	1.63	2.48	1.40	3.39
Livestock price [c]	0.07	0.78	–0.04	–0.20	0.77	0.65	0.38	0.60
Food price [d]	0.06	0.04	–0.02	0.13	0.00	0.10	–0.11	0.36
Per-capital welfare [e]	0.00	–0.05	–0.05	–0.05	–0.06	0.00	–0.01	–0.11
Regional per-capita welfare								
United States	0.01	–0.05	0.04	0.03	–0.04	–0.08	0.03	0.03
Canada	0.06	–0.03	0.16	0.15	0.03	–0.01	0.19	0.10
European Community	–0.01	0.00	0.00	–0.06	–0.02	–0.08	–0.07	–0.12
Japan	0.03	–0.01	0.06	0.06	0.07	0.04	0.11	0.03
Other East Asia	0.02	–0.13	–0.15	0.09	–0.03	0.09	0.11	–0.07
Southeast Asia	–0.13	–0.07	–0.08	–0.54	–0.42	–0.53	–0.60	–1.00
Australia plus New Zealand	0.07	–0.01	0.10	–0.02	0.18	–0.03	0.12	0.08
Rest-of-World	0.01	–0.02	–0.03	–0.05	–0.05	0.03	–0.01	–0.05

[a] Derived with the Future Agricultural Resources Model by imposing results from general circulation models (GCMs) on 1990 economic conditions. The GCMs (in ascending order by change in mean global temperature) are the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL), the Hadley Centre, Oregon State University, GFDL, Goddard Institute for Space Studies, and the United Kingdom Meteorological Office.
[b] Derived from Fisher quantity and price indices of world changes in wheat, other grains, and non-grains production. World changes in wheat, other grains, and non-grains quantities and prices are quantity-weighted sums of regional changes.
[c] Derived as Fisher quantity and price indices of regional changes.
[d] Derived as population-weighted sums of regional changes. Regional percent changes are in turn derived from Fisher quantity and price indices of wheat, other grains, non-grains, livestock, fish-meat-milk, and other processed foods consumed directly by households.
[e] Derived as population-weighted sums of regional changes.

and Australia plus New Zealand. Economic impacts exhibiting no statistically significant (at the 5% level) trend with respect to increases in mean global temperature are the world food price as well as per-capita welfare in the United States, Other East Asia, and Rest-of-World.

FARM estimates, estimates of summary functions, and 95, 67, and 33% confidence limits of the summary estimates are depicted in Figures 7–11. Impacts and

Table IX

Increases in mean global temperature and annual production of agricultural commodities, per-capita consumption of food, and per-capita welfare relative to 1990 economic conditions: Summary functions of impacts estimated with the Future Agricultural Resources Model

Dependent variable	Parameter on change in temperature [a]	Adjusted R-squared [b]	Degrees of freedom	Average standard error
World crop production	–0.223*** (–6.656)	0.832	7	0.291
World livestock production	–0.077*** (–9.461)	0.935	7	0.071
World food consumption	–0.021* (–2.683)	0.492	7	0.068
World crop prices	0.577*** (9.809)	‘0.930	7	0.512
World livestock prices	0.141* (3.487)	0.604	7	0.351
World food prices	0.026 (1.776)	0.340	7	0.128
Per-capita welfare:				
World	–0.015* (–3.431)	0.541	7	0.039
United States	–0.001 (–0.265)	0.007	7	0.046
Canada	0.030* (2.952)	0.437	7	0.090
European Community	–0.017*** (–6.360)	0.876	7	0.023
Japan	0.018** (4.225)	0.644	7	0.038
Other East Asia	–0.003 (–0.273)	–0.030	7	0.104
Southeast Asia	–0.157*** (–9.694)	0.935	7	0.141
Australia plus New Zealand	0.023* (2.558)	0.389	7	0.078
Rest-of-World	–0.008 (–2.137)	0.261	7	0.032

[a] Parentheses indicate t-statistics. One, two, and three asterisks (*, **, ***) indicate statistical significance at the 5, 1, and 0.1% levels, respectively.
[b] Because the models lack intercept terms, the calculation of the coefficient of multiple determination, R^2, is $R^2 = 1 - \hat{e}'\hat{e}/\mathbf{y}'\mathbf{y}$, where $\hat{e}$ is a vector of estimated errors and $\mathbf{y}$ is a vector of dependent variables. The adjusted $R^2 = 1 - (\hat{e}'\hat{e}/n - k)/(\mathbf{y}'\mathbf{y}/(n-1))$, where n is the total number of observations and k is the number of independent variables.

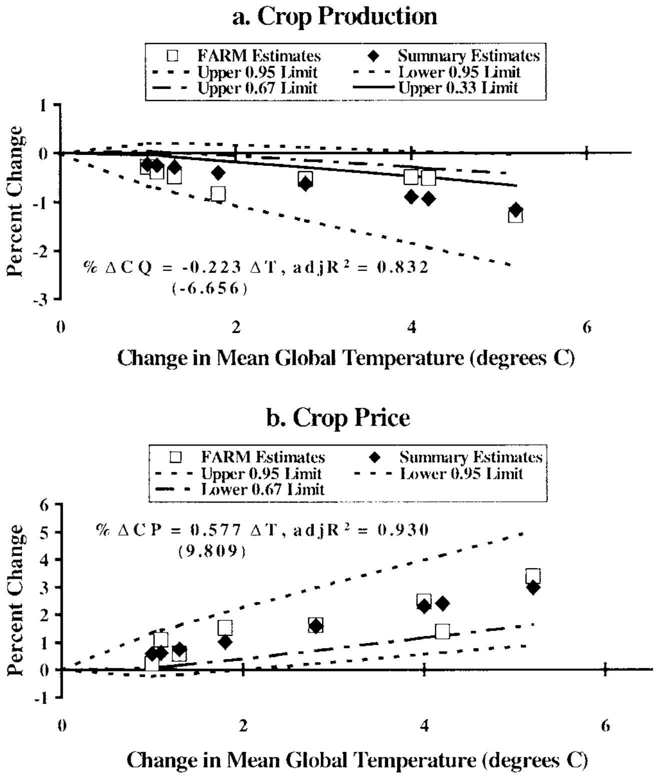

Figure 7. Estimated impacts of global climate change on world crop production and prices. Equations give parameter estimates (with student t-statistics in parentheses) for summary functions of FARM estimates regressed on increases in mean global temperature.

their confidence limits are summarized further in Table X. Directions of impact, either *increase* or *decrease*, are determined by the signs (positive or negative, respectively) of the estimated parameters on change in temperature presented in Table IX irrespective of statistical significance. As such they mirror the upward and downward trends reported above. Impacts for statistically insignificant (at the 5% level) trends are as follows: the world food price *increases*, while per-capita welfare in the United States, Other East Asia, and Rest-of-World regions *decreases*.

Sizes of impact for 1.0 and 5.2 °C increases in mean global temperature are equal to the absolute value of the estimated parameters on change in temperature multiplied by increases in temperature of 1.0 and 5.2 °C, respectively. They are generally less than 0.5%. The only exceptions are for world crop prices at 1.0 and 5.2 °C and for world crop production, world livestock price, and per-capita income in Southeast Asia at 5.2 °C. World crop impacts (both quantity and price) are larger than world livestock impacts. And both crop and livestock impacts are larger than world food impacts, which are in turn larger than the impacts on world per-capita welfare.

Table X

Increases in mean global temperature and annual production of agricultural commodities, per-capita consumption of food, and per-capita welfare relative to 1990 economic conditions: Direction, average size, and confidence of impacts estimated with the Future Agricultural Resources Model

Dependent variable	Impact direction and size (%) at:		95% Confidence limits (±%) at:		Confidence of impact direction [a]
	1.0 °C	5.2 °C	1.0 °C	5.2 °C	
World crop production	Decrease; 0.22	1.16	0.44	1.15	Medium below 1.6 °C; high from 1.6 to 5.0 °C; very high above 5.0 °C
World livestock production	Decrease; 0.08	0.40	0.12	0.33	High below 3.0 °C; very high above 3.0 °C
World food consumption	Decrease; 0.02	0.11	0.08	0.22	Low below 3.5 °C; medium above 3.5 °C
World crop prices	Increase; 0.58	3.00	0.78	2.07	High below 1.9 °C; very high above 1.9 °C
World livestock prices	Increase; 0.14	0.73	0.68	1.81	Low over entire range of temperature increases
World food prices	Increase: 0.03	0.14	0.16	0.41	Low over entire range of temperature increases
Per-capita welfare:					
World	Decrease; 0.02	0.08	0.06	0.15	Low below 3.0 °C; medium above 3.0 °C
United States	Decrease; 0.00	0.01	0.07	0.19	Low over entire range of temperature increases
Canada	Increase; 0.03	0.16	0.15	0.40	Low over entire range of temperature increases
European Community	Decrease; 0.02	0.09	0.04	0.10	Medium below 2.0 °C; high above 2.0 °C
Japan	Increase; 0.02	0.09	0.06	0.15	Low below 1.9 °C medium above 1.9 °C
Other East Asia	Decrease; 0.00	0.02	0.19	0.50	Low over entire range of temperature increases
Southeast Asia	Decrease; 0.16	0.82	0.24	0.62	High below 2.4 °C; very high above 2.4 °C
Australia plus New Zealand	Increase; 0.02	0.12	0.12	0.32	Low over entire range of temperature increases
Rest-of-World	Decrease; 0.01	0.04	0.05	0.13	Low over entire range of temperature increases

[a] ‘Very high’, ‘high’, and ‘medium’ indicate that 95, 67, and 33% confidence limits, respectively, of the estimated average impacts do not encompass zero (e.g., the horizontal axis). ‘Low’ indicates that the 33% confidence limits of the estimated average impacts encompass zero. Critical values of $t_{(7,0.025)}$, $t_{(7,0.165)}$, and $t_{(7,0.335)}$ are 2.365, 1.535, and 1.041, respectively.

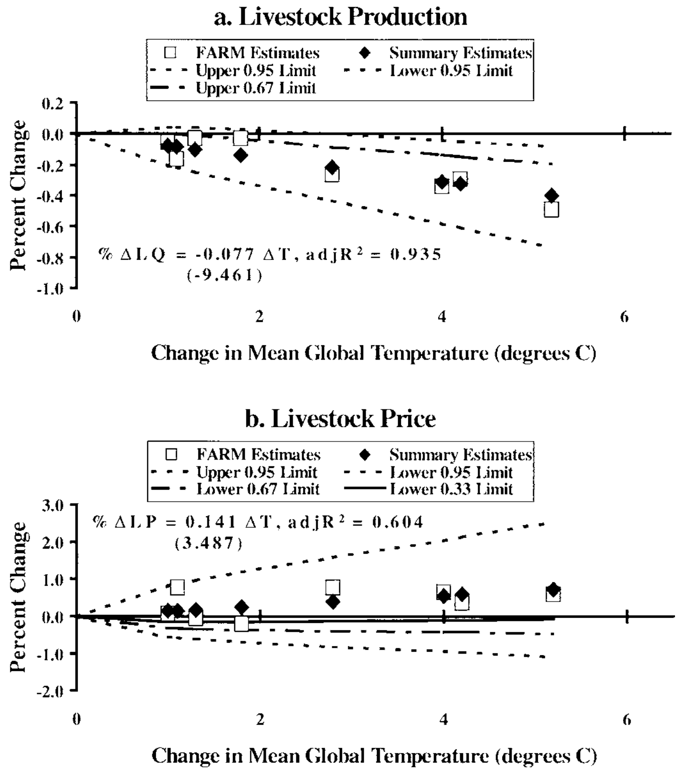

Figure 8. Estimated impacts of global climate change on world livestock production and prices. Equations give parameter estimates (with student t-statistics in parentheses) for summary functions of FARM estimates regressed on increases in mean global temperature.

As explicitly assumed, 95% confidence limits are larger when mean global temperature increases by 5.2 °C than by 1.0 °C. They are typically less than ±1.0%. The only exceptions are for crop production, crop price, and livestock price at 5.2 °C. Confidence in the impacts is *low* over the entire range of temperature increases for world livestock and world food prices, and per-capita welfare in the United States, Canada, Other East Asia, Australia plus New Zealand, and Rest-of-World region. Confidence in the impacts on world food consumption and per-capita welfare in Japan is *low* for some of the temperature increases. Confidence in the impacts on world crop production, world food consumption, world per-capita welfare, and per-capita welfare in the European Community and Japan is *medium* for some of the temperature increases. Confidence in the impacts on world crop production, world livestock production, world crop price, and per-capita welfare in Southeast Asia is *high and very high* for some of the temperature increases. Confidence increases as mean global temperature increases. Confidence in the impacts of temperature increases equal to or less than 1.8 °C, for example, is mostly *low*. Exceptions include world crop production (*medium* to *high*), world livestock

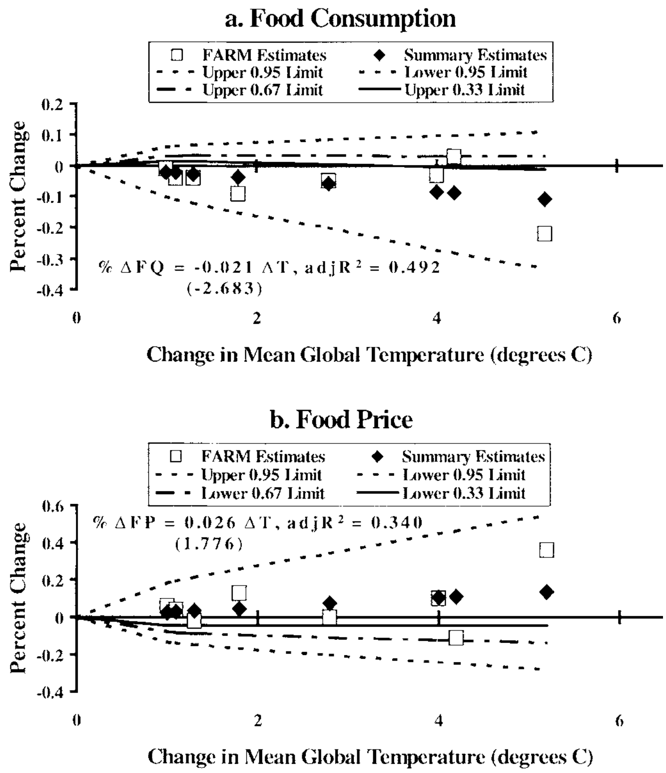

Figure 9. Estimated impacts of global climate change on world food consumption and prices. Equations give parameter estimates (with student t-statistics in parentheses) for summary functions of FARM estimates regressed on increases in mean global temperature.

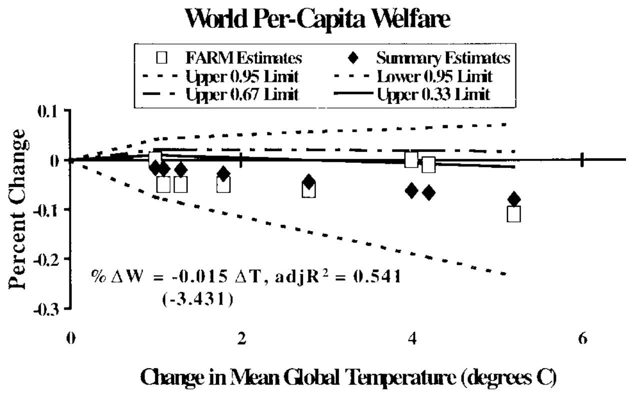

Figure 10. Estimated impacts of global climate change on world and regional per-capita welfare. The equation gives parameter estimates (with student t-statistics in parentheses) for summary functions of FARM estimates regressed on increases in mean global temperature.

production (*high*), world crop price (*high*), and per-capita welfare in the European Community (*medium*) and Southeast Asia (*high*).

3.1.2. *Discussion*

The trends depicted in Table IX indicate that increases in mean global temperature could cause world crop and livestock production, world food consumption, and world per-capita welfare to fall, on average, and world crop and livestock prices to rise. Declines in crop production range on average from 0.22 to 1.16% for temperature increases of 1.0 and 5.2 °C, respectively (Table X). Compared, say, to a 2.0% growth rate in TFP for crop production (see Section 2.1.3 above), these are relatively large impacts. Declines in world per-capita welfare range on average from 0.02 to 0.08%. These declines are relatively small even when compared to conservative rates of growth in per-capita welfare, e.g., 1.8% (see Section 2.1.3 above). This is not too surprising. The impact on world per-capita welfare is an aggregate of opposing impacts on regional per-capita welfare, which for Southeast Asia and Canada, range on average from –0.16 to +0.03%, respectively, at 1.0°C and from –0.82 to +0.16%, respectively, at 5.2 °C. The regional changes are larger both in absolute terms and when compared, say, to the growth rates of per-capita welfare assumed in the scenarios with improved economic conditions, e.g., 1.8 and 2.8% for Canada and Southeast Asia, respectively.*

The relative sizes of the trends are as expected. The decline in world per-capita welfare is smaller than the decline in food consumption because food is only one of many goods and services that people consume. The decline in food consumption is smaller than the declines in crop and livestock production because people forego consumption of other goods and services before food, which in turn encourages farmers to maintain production of food-related products and to reduce production of non-food-related products. In addition, imports from regions where climate change facilitates agriculture help to offset production losses where farmer adaptations fail to maintain food-related agricultural production at no-climate-change levels.

The 95% confidence limits depicted in Figures 7–11 and summarized in Table X indicate that in many instances the economic uncertainty due to variable projections of climate is fairly large. In this analysis, for example, the limits of most economic impacts encompass both positive and negative values for all increases in mean global temperature considered. Exceptions include world crop production, world livestock production, world crop price, and per-capita welfare in Southeast Asia. Analysis of the direction of impacts with 67 and 33% confidence limits (Table X) further indicates that variable projections of climate contribute to uncertainty of many economic impacts. Confidence in most impacts, for example, is *low* over at least some of the increases in mean global temperature. Exceptions

* Growth rates for regional per-capita income can be approximated by subtracting growth rates in population from growth rates of gross domestic product (see Table V).

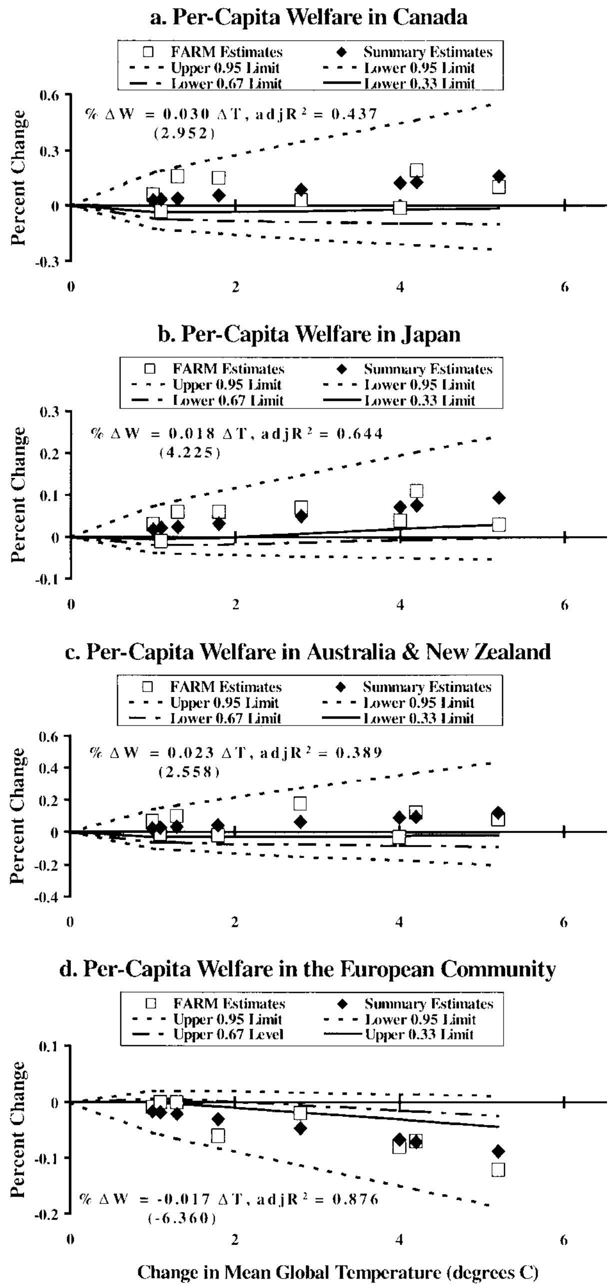

Figure 11. Estimated impacts of global climate change on per-capita welfare in specific regions. Equations give parameter estimates (with student t-statistics in parentheses) for summary functions of FARM estimates regressed on increases in mean global temperature.

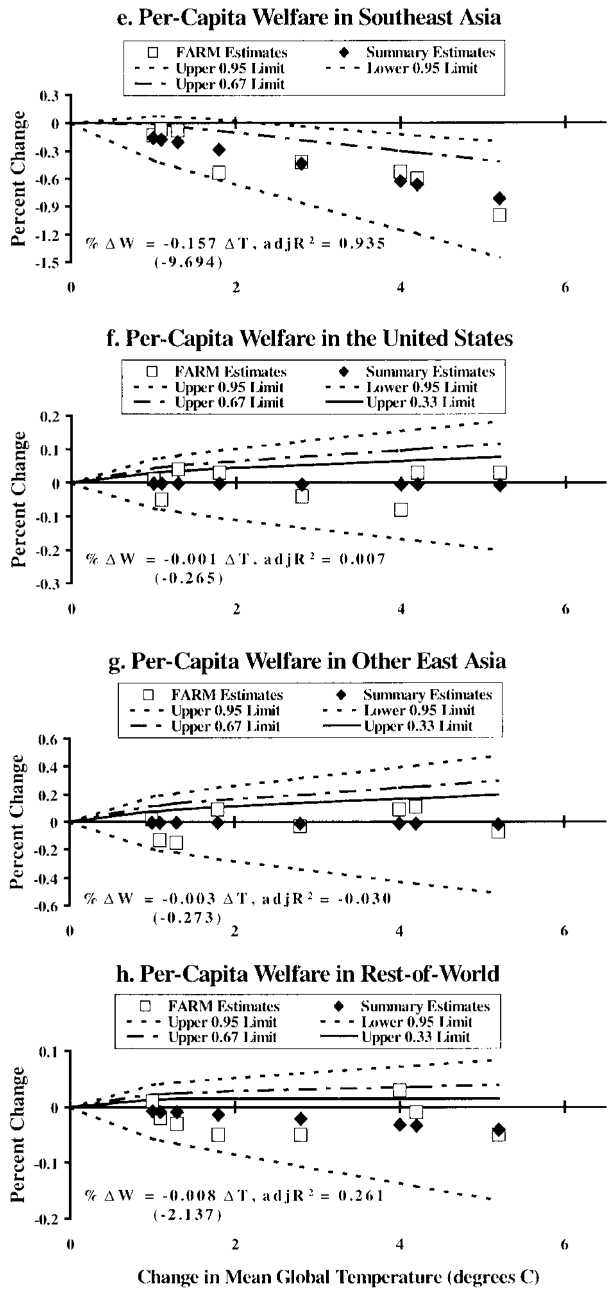

Figure 11. (Continued).

include world crop production, world livestock production, world crop price, and per-capita welfare in the European Community and Southeast Asia.

On a somewhat brighter note, the results indicate that it is possible to contend with at least some of the uncertainty due to variable projections in climate. Knowing the statistical significance of average trends with respect to increases in mean global temperature, for example, reduces the uncertainty associated with an economic impact somewhat. The uncertainty surrounding economic impacts that exhibit statistically significant upward or downward trends is lower, all else equal, than the uncertainty surrounding economic impacts without statistically significant trends because the likely direction of impacts is known with the former, but is unknown with the latter. Unfortunately, a statistically significant (at the 5% level) trend does not guarantee a confidence level better than *low* even when mean global temperature increases by 5.2° (see livestock prices and per-capita welfare in Canada and Australia plus New Zealand). Nevertheless, confidence in some economic impacts are better than *low* even when increases in mean global temperature are equal to or less than 1.8 °C. In this analysis, these include decreases in world crop production (*medium* to *high*), decreases in world livestock production (*high*), increases in world crop price (*high*), and decreases in per-capita welfare in the European Community (*medium*) and Southeast Asia (*high*).

A few caveats are in order. First, the 95% confidence limits depend in part on the assumptions about heteroskedasticity. In the models presented here, the residuals are assumed to increase as the change in temperature increases, e.g., variance$(u_i) = \sigma^2|T_i|$. If the residuals were assumed to increase as the square of the temperature increases, e.g., variance$(u_i) = \sigma^2 T_i^2$, then the 95% confidence limits would be narrower at low increases in temperature and wider at high increases in temperature. The trend would also shift somewhat. Second, some of the variability in the results may be due to outdated projections of climate. Except for one scenario from 1995 and another from 1996–1997, the climate scenarios in the analysis are relatively old – from the 1980s and early 1990s. The most variable climate input underlying this analysis, however, is regional precipitation (Table IV). And, though simulations of the climate system and its changes have improved, the uncertainty in future projections of water vapor and clouds is still relatively high (Albritton et al., 2001). Hence, although including more recent GCM results might reduce the variability of the estimated impacts somewhat, doing so at this time might not provide much additional insight.

3.2. IMPACTS OF CLIMATE CHANGE UNDER IMPROVED ECONOMIC CONDITIONS

FARM's estimated economic impacts of increases in mean global temperature ranging from 1.0 to 1.8 °C in combination with improved economic conditions are presented in Table XI. They are measured as percent changes relative to a scenario with improved economic conditions but without climate change. Variability is indi-

Table XI

Estimated annual economic impacts (% change) of climate change relative to improved economic conditions [a]

Economic variable	Temperature change (°C)			
	1.0	1.1	1.3	1.8
World				
Crop production [b]	–0.32	–0.27	–1.14	–1.41
Livestock production [c]	–0.02	0.01	0.03	0.21
Food consumption [d]	0.00	0.23	0.19	–0.40
Crop prices [b]	–0.05	0.16	0.04	3.05
Livestock prices [c]	0.37	0.12	–0.11	–1.56
Food prices [d]	0.09	–0.51	–0.49	1.21
Per-capita welfare [e]	0.20	0.09	0.08	–0.10
Regional per-capita welfare				
United States	0.02	0.00	0.09	0.06
Canada	0.15	–0.04	0.38	0.39
European Community	0.02	0.06	0.07	0.00
Japan	0.04	0.07	0.12	0.09
Other East Asia	0.03	0.22	0.12	0.11
Southeast Asia	0.05	0.04	0.15	–0.06
Australia plus New Zealand	0.12	–0.12	–0.02	–0.34
Rest-of-World	0.01	0.07	0.05	–0.18

[a] Derived with the Future Agricultural Resources Model by imposing results from General Circulation Models (GCMs) on hypothetical projections of improved economic conditions. The GCMs (in ascending order by change in mean global temperature) are the University of Illinois at Urbana-Champaign, the Max Planck Institute, the Geophysical Fluid Dynamics Laboratory (GFDL), and the Hadley Centre.
[b] Derived from Fisher quantity and price indices of world changes in wheat, other grains, and non-grains production. World changes in wheat, other grains, and non-grains quantities and prices are quantity-weighted sums of regional changes.
[c] Derived as Fisher quantity and price indices of regional changes.
[d] Derived as population-weighted sums of regional changes. Regional percent changes are in turn derived from Fisher quantity and price indices of wheat, other grains, non-grains, livestock, fish-meat-milk, and other processed foods consumed directly by households.
[e] Derived as population-weighted sums of regional changes.

cated by the fact that the impacts on each economic variable do not monotonically increase or decrease as mean global temperature increases. In addition, most economic variables incur both positive and negative impacts over the range of mean increases in temperature.

3.2.1. *Results*

Summary functions that indicate how improved economic conditions might modify the economic impacts of global warming (by 1.0 to 1.8 °C) are presented in Table XII. Note that the parameters on the change in temperature are identical to those in Table X. The t-statistics for these parameters, however, differ; except for summary functions for per-capita welfare in Japan and Southeast Asia they are smaller in Table XII than in Table X. The parameter of greatest interest, however, is for the dummy temperature variable (β_1 in Equation (4)). It indicates whether improved economic conditions cause the impact trends associated with increases in mean global temperature to change. Economic impacts that exhibit statistically significant (at the 5% level) changes in trend include world crop production, world livestock production, and per-capita welfare in Canada, the European Community, Japan, Other East Asia, and Southeast Asia. Per-capita welfare in the United States and Australia plus New Zealand exhibit changes in trend that are statistically significant at the 10% level. These changes are generally positive. The two exceptions are world crop production and per-capita welfare in Australia plus New Zealand.

The changes in trend generate changes in the general direction of some economic impacts. Examples include world livestock production, world food consumption, world livestock price, world per-capital welfare, and per-capita welfare in the United States, European Community, Other East Asia, Southeast Asia, and Australia plus New Zealand as mean global temperature increases by 1.0 to 5.2 °C (compare Tables X and XIII). As under 1990 economic conditions, confidence in the direction of economic impacts as temperature increases by 1.8 °C or less is mostly *low*. Exceptions include world crop production (*very high*), world crop price (*low* to *medium*), and per-capita welfare in the United States (*low* to *medium*), Japan (*very high*), European Community (*medium*) and Other East Asia (*medium*). Confidence in the impacts as temperature increases by 1.8 °C or less also changes under improved economic conditions. A comparison of results in Tables X and XIII indicates, for example, that confidence in impacts on world crop production and per-capita welfare in the United States, Canada, Japan, and Other East Asia qualitatively increases. On the other hand, confidence in impacts on world livestock production, world crop price, and per-capita welfare in Southeast Asia qualitatively decreases. Confidence in the other impacts is qualitatively the same, primarily *low*. Confidence in the impacts on per-capita welfare in the European Community, however, switches from *medium* for a *decrease* in direction to *medium* for an *increase* in direction.

3.2.2. *Discussion*

The results indicate that economic conditions at the time of impact influence the direction and size of as well as the confidence in estimated economic impacts of identical projections of climate change. This adds an additional source of uncertainty to those typically associated with variable projections of economic activity, e.g., the corresponding variable projections of atmospheric concentrations and

Table XII

Increases in mean global temperature and annual production of agricultural commodities, per-capita consumption of food, and per-capital welfare: Summary functions of impacts estimated with the Future Agricultural Resources Model, linear functional form with dummy temperature variable for improved economic conditions

Dependent variable	Change in temperature [a]	Dummy temperature variable [a]	Adjusted R-squared [b]	Degrees of freedom	Average standard error
World crop production	–0.223*** (–5.954)	–0.381* (2.988)	0.833	10	0.326
World livestock production	–0.077*** (–8.765)	0.121** (4.050)	0.889	10	0.077
World food consumption	–0.021 (–1.087)	0.025 (0.377)	0.005	10	0.168
World crop prices	0.577*** (6.046)	0.038 (0.118)	0.787	10	0.830
World livestock prices	0.141* (2.436)	–0.348 (–1.772)	0.311	10	0.555
World food prices	0.026 (0.511)	0.032 (0.181)	–0.019	10	0.446
Per-capital welfare:					
World	–0.015* (–2.228)	0.033 (1.389)	0.173	10	0.060
United States	–0.001 (–0.283)	0.034 (2.024)	0.246	10	0.043
Canada	0.030* (2.229)	0.139* (2.992)	0.632	10	0.118
European Community	–0.017*** (–5.069)	0.046** (4.041)	0.763	10	0.029
Japan	0.018*** (4.510)	0.043* (3.147)	0.760	10	0.035
Other East Asia	–0.003 (–0.289)	0.096* (2.476)	0.286	10	0.099
Southeast Asia	–0.157*** (–10.632)	0.192** (3.803)	0.916	10	0.129
Australia plus New Zealand	0.023 (1.737)	–0.092 (–2.052)	0.325	10	0.115
Rest-of-World	–0.008 (–1.035)	–0.002 (–0.064)	0.016	10	0.067

[a] Parentheses indicate t-statistics. One, two, and three asterisks (*, **, ***) indicate statistical significance at the 5, 1, and 0.1% levels, respectively.

[b] Because the models lack intercept terms, the calculation of the coefficient of multiple determination, R^2, is $R^2 = 1 - \hat{e}'\hat{e}/\boldsymbol{y}'\boldsymbol{y}$, where $\hat{e}$ is a vector of estimated errors and $\boldsymbol{y}$ is a vector of dependent variables. The adjusted $R^2 = 1 - (\hat{e}'\hat{e}/n - k)/(\boldsymbol{y}'\boldsymbol{y}/(n-1))$, where n is the total number of observations and k is the number of independent variables.

Table XIII

Increases in mean global temperature and annual production of agricultural commodities, per-capita consumption of food, and per-capita welfare relative to improved economic conditions: Direction, average size, and confidence of impacts estimated with the Future Agricultural Resources Model

Dependent variable	Impact direction and size (%) at:		95% Confidence limits (±%) at:		Confidence of impact direction[a]
	1.0 °C	1.8 °C	1.0 °C	1.8 °C	
World crop production	Decrease; 0.60	1.09	0.59	0.89	Very high 0.0 to 1.8 °C
World livestock production	Increase; 0.04	0.08	0.14	0.21	Low from 0.0 to 1.8 °C
World food consumption	Increase; 0.00	0.01	0.31	0.47	Low from 0.0 to 1.8 °C
World crop prices	Increase; 0.62	1.11	1.50	2.27	Low below 1.4 °C medium 1.4 to 1.8 °C
World livestock prices	Decrease; 0.21	0.37	0.98	1.49	Low from 0.0 to 1.8 °C
World food prices	Increase; 0.06	0.10	0.84	1.28	Low from 0.0 to 1.8 °C
Per-capita welfare:					
World	Increase; 0.02	0.03	0.11	0.16	Low from 0.0 to 1.8 °C
United States	Increase; 0.03	0.06	0.07	0.11	Low below 1.1 °C; medium 1.1 to 1.8 °C
Canada	Increase; 0.17	0.30	0.24	0.36	High from 0.0 to 1.8 °C
European Community	Increase; 0.03	0.05	0.05	0.08	Medium from 0.0 to 1.8 °C
Japan	Increase; 0.06	0.11	0.06	0.09	Very high from 0.0 to 1.8 °C
Other East Asia	Increase; 0.09	0.17	0.19	0.28	Medium from 0.0 to 1.8 °C
Southeast Asia	Increase; 0.03	0.06	0.22	0.33	Low from 0.0 to 1.8 °C
Australia plus New Zealand	Decrease; 0.07	0.12	0.22	0.32	Low from 0.0 to 1.8 °C
Rest-of-World	Decrease; 0.01	0.02	0.12	0.19	Low from 0.0 to 1.8 °C

[a] 'Very high', 'high', and 'medium' indicate that 95, 67, and 33% confidence limits, respectively, of the estimated average impacts do not encompass zero (e.g., the horizontal axis). 'Low' indicates that the 33% confidence limits of the estimated average impacts encompass zero. Critical values of $t_{(10,0.025)}$, $t_{(10,0.165)}$, and $t_{(10,0.335)}$ are 2.228, 1.526, and 1.018, respectively.

climatic impacts of greenhouse gas emissions over time. One also might have expected that improved economic conditions would moderate the impacts of global warming. Results from the scenario of improved economic conditions simulated in this analysis suggest, however, that may not always be the case. World crop production in the scenarios with improved economic conditions, for example, declines on average by 0.60% for each 1.0 °C-increase in mean global temperature, which is *more* than the 0.22% in the scenarios with 1990 economic conditions. This offsets almost all the 0.70% average worldwide growth rate of total factor productivity of crops assumed in the scenario of improved economic conditions.

In general improved economic conditions do appear to moderate negative or reinforce the positive impacts of climate change on per-capita welfare. But again there is a potential exception. As simulated in this analysis, improved economic conditions reduce (at the 10% significance level) per-capita welfare in Australia plus New Zealand on average as mean global temperature increase by 1.0 to 1.8 °C. The explanation is as follows. Under the improved economic conditions assumed in this analysis, the share of income generated by agriculture in Australia plus New Zealand increases from 5.1 to 7.7% as exports to Japan, Other East Asia, and Southeast Asia expand. When combined with the climate change assumptions in this analysis, agricultural exports from Australia plus New Zealand to Japan, Other East Asia, and Southeast Asia decline on average, causing crop production and agricultural income in Australia plus New Zealand to decline, respectively, by 5.3 and 3.4% on average. These declines in agricultural income are too large to be completely offset by rising incomes in other sectors.

3.3. IMPACTS OF CO_2 FERTILIZATION UNDER IMPROVED ECONOMIC CONDITIONS

Estimates of the impacts of a 150-ppmv increase in atmospheric CO_2 on 1990 and improved economic conditions are presented in Table XIV. Under both sets of conditions, world crop and livestock production, world food consumption, and world per-capita welfare increase while world crop, world livestock, and world food prices decline. The absolute values of world impacts are larger when CO_2 fertilization is simulated simultaneously with improved economic conditions. World crop production, livestock production, food consumption, and per-capita welfare increase by 1.52, 0.62, 1.25, and 0.48%, respectively, under 1990 economic conditions, and by 2.70, 0.92, 1.77, and 0.55%, respectively, under improved economic conditions.

The effects of CO_2 fertilization on per-capita welfare are positive in all regions under 1990 economic conditions. They are relatively large in developing regions such as Other East Asia and Southeast Asia (0.81 and 0.60%, respectively) or in regions comprised primarily of developing countries such as the Rest-of-World region (0.43%), where agriculture's share of total production is relatively large. Changes in per-capita welfare in developed countries range from 0.02% in Aus-

Table XIV
Estimated annual economic impacts (% change) of CO_2 fertilization[a]

Economic variable	1990 Economy	Improved economic conditions
World		
Crop production[b]	1.52	2.70
Livestock production[c]	0.62	0.92
Food consumption[d]	1.25	1.77
Crop prices[b]	–5.60	–9.63
Livestock prices[c]	–1.10	–2.10
Food prices[d]	–2.61	–4.79
Per-capita welfare[e]	0.48	0.55
Regional per-capita welfare		
United States	0.07	0.05
Canada	0.09	0.12
European Community	0.14	0.11
Japan	0.21	0.16
Other East Asia	0.81	0.48
Southeast Asia	0.60	0.68
Australia plus New Zealand	0.02	–0.20
Rest-of-World	0.43	0.62

[a] Derived with the Future Agricultural Resources Model by imposing yield changes on 1990 economic conditions and hypothetical projections of improved economic conditions. Based on a 150-ppmv increase in the atmospheric concentration of CO_2.
[b] Derived from Fisher quantity and price indices of world changes in wheat, other grains, and non-grains production. World changes in wheat, other grains, and non-grains quantities and prices are quantity-weighted sums of regional changes.
[c] Derived as Fisher quantity and price indices of regional changes.
[d] Derived as population-weighted sums of regional changes. Regional percent changes are in turn derived from Fisher quantity and price indices of wheat, other grains, non-grains, livestock, fish-meat-milk, and other processed foods consumed directly by households.
[e] Derived as population-weighted sums of regional changes.

tralia plus New Zealand to 0.21% in Japan. The effects of CO_2 fertilization on per-capita welfare are *not* positive in all regions when combined with improved economic conditions. Per-capita income in Australia plus New Zealand actually declines by 0.20%. In addition, changes in per-capita welfare for most of the other regions are smaller under improved rather than 1990 economic conditions. The only regions where per-capita welfare increases when improved rather than 1990 economic conditions are simulated with CO_2 fertilization are Canada, Southeast Asia, and the Rest-of-World.

3.3.1. *Discussion*

Improved economic conditions reinforce the beneficial effects of CO_2 fertilization aggregated at the world level. World agricultural production, food consumption, and per-capita welfare are higher, while world prices are lower when improved rather than 1990 economic conditions are simulated. Improved economic conditions do not necessarily reinforce the beneficial effects of CO_2 fertilization at regional levels. Percent increases in per-capita welfare are smaller in four regions and per-capita welfare actually declines in Australia plus New Zealand when improved rather than 1990 economic conditions are simulated.

The CO_2-fertilization-induced and climate-induced declines in Australia plus New Zealand have the same origin. Under the improved economic conditions assumed in this analysis, the share of income generated by agriculture in Australia plus New Zealand increases from 5.1 to 7.7% as exports to Japan, Other East Asia, and Southeast Asia expand. When combined with the CO_2-fertilization assumptions in this analysis, agricultural exports from Australia plus New Zealand to Japan, Other East Asia, and Southeast Asia decline, causing crop production and agricultural income in Australia plus New Zealand to decline, respectively, by 9.3 and 14.2% on average. Also note that the fall in agricultural income is aggravated by a 9.2% decline in crop prices in the CO_2-fertilization scenario, but is moderated somewhat by slightly higher prices in the climate change scenarios.

Again a few caveats are in order. First, although CO_2 fertilization is expected to increase crop yields, the magnitude of this effect is not known with certainty. For example, experimental yield responses for many crops to 700 ppmv of atmospheric CO_2 (approximately double the 1995 concentration) average 30% higher, with a range of –10 to +80% (Reilly et al., 1996). In addition, knowledge of the benefits of elevated CO_2 on many tropical crops is incomplete (Gitay et al., 2002). Second, the estimated yield changes used in this analysis are based on crop modeling exercises rather than field experiments. These yield changes are, however, in line with recent free-air CO_2 enrichment experiments as cited by Gitay et al. (2002), e.g., under 550 ppmv cotton yields increase by 48% and spring wheat yields (also under optimal N and water) increase by 15 to 16%. Third, this paper ignores the potential agronomic impacts of CO_2 fertilization on permanent pastures. This bias is offset somewhat, however, by the fact that at least some forage crops contain lower concentrations of protein when grown under higher concentrations of CO_2

(Reilly et al., 1996). Lastly, the results presented here overestimate the agricultural benefits of fossil fuel emissions by including CO_2 fertilization while excluding the detrimental effects of various pollutants, such as ozone and sulfur dioxide. On the other hand, the potential beneficial effects of rising levels of nitrogen deposition from fossil fuel emissions on crop growth also are not taken into account. None of these limitations, however, are likely to affect the main points of this analysis.

4. Summary and Conclusions

Because of many uncertainties, the IPCC has given quantitative estimates of agriculturally related economic impacts of greenhouse gas emissions low confidence (Gitay et al., 2001). A major source of uncertainty is our inability to accurately project future changes in economic activity, emissions, and climate. Although this source of uncertainty will always exist, the development of ways to quantify and categorize its impacts on estimates of economic activity will increase our ability to cope with it.

This paper first focuses on the extent to which variable projections of climate might generate uncertainty in agriculturally related economic impacts. To analyze this I estimate average economic impacts and confidence limits of eight GCM-based projections of climate change. Projected increases in mean global temperature range from 1.0 to 5.2 °C. Economic impacts include world crop and livestock production, world food consumption, world per-capita income, and per-capita income in the United States, Canada, European Community, Japan, Other East Asia, Southeast Asia, Australia plus New Zealand, and Rest-of-World. The paper then focuses on the extent to which estimated economic effects of climate change and CO_2 fertilization depend on economic conditions at the time of impact. To analyze this I compare average economic impacts and confidence limits estimated by imposing identical scenarios of climate change and CO_2 fertilization on two sets of economic conditions – 1990 and improved.

Economic uncertainty due to variable projections of climate is found to be fairly large. This is indicated by *low* levels of confidence in the direction of most of the economic impacts analyzed as mean global temperature increases by 1.8 °C or less, assuming either 1990 or improved economic conditions. Confidence in the direction of economic estimates improves when mean global temperature increases by 2.8 to 5.2 °C assuming 1990 economic conditions. Economic uncertainty due to variable projections of economic activity also is found to be fairly large. Economic conditions at the time of impact influence the direction and size of as well as the confidence in estimated economic impacts of identical projections of climate change. For example, climate change causes per-capita welfare in the European Community to decrease under 1990 economic conditions, but to increase under improved economic conditions. The confidence in both cases is *medium* with respect to variable projections in climate. Confidence in other economic impacts, however, are qualitatively different under improved than under 1990 economic conditions. Increases in world agricultural production, food consumption, and per-capita welfare are also higher when CO_2 fertilization is simulated under improved rather than 1990 economic conditions. This adds an additional source of uncertainty to those typically associated with variable projections of economic activity, e.g., the corresponding variable projections of atmospheric concentrations and impacts of greenhouse gas emissions over time.

Improved economic conditions are not necessarily a panacea to potential greenhouse-gas-induced damages. In fact, in some regions, impacts of climate change or CO_2 fertilization that are beneficial under current economic conditions may be detrimental under improved economic conditions (relative to the new economic base). Per-capita welfare in Australia plus New Zealand behaves this way in this analysis. These negative effects are attributed to the relatively large share of income generated by agricultural exports in Australia plus New Zealand under the improved economic conditions assumed in this analysis. When combined with the climate-change and CO_2-fertilization scenarios, agricultural exports from Australia plus New Zealand decline on average. Resultant declines in agricultural income in Australia plus New Zealand are too large to be completely offset by rising incomes in other sectors. Of course this may not occur in alternative scenarios of economic conditions. Nevertheless it does indicate that regions that rely on agricultural exports for relatively large shares of their income are vulnerable not only to direct climate-induced agricultural damages, but also to positive impacts induced by greenhouse gas emissions elsewhere.

In this analysis, greenhouse gas emissions have the most consistent impacts on world crop production. Increases in mean global temperature cause world crop production to decrease by 0.22 ($\pm$0.44) and 0.60 ($\pm$0.59) percent per 1.0 °C under 1990 and improved economic conditions, respectively, and the confidence with respect to variable projections of climate is *medium* or greater in both instances. CO_2 fertilization due to a 150-ppmv increase in atmospheric CO_2, on the other hand, causes world crop production to increase by 1.52 and 2.70% under 1990 and improved economic conditions. Impacts are also larger on world crop production than on world livestock production, food consumption, or per-capita welfare. This suggests that crop production may be a fairly robust indicator of the potential impacts of greenhouse gas emissions. Downstream impacts on food consumption or economic welfare may be less effective indicators because they have relatively smaller absolute values thereby making it more difficult to isolate them from the uncertainty generated by variable projections in climate.

The results reported here are consistent with many earlier results. First, results here show that increases in mean global temperature ranging from 2.8 to 5.2 °C are likely to reduce world agricultural production, food security, and economic welfare. How improved economic conditions might alter these impacts, however, is not investigated. Disagreements about the impacts of smaller increases in mean global temperature are not completely resolved. On the one hand, results here show that under various economic conditions climate change is likely to cause world crop production to fall and the price to rise when increases in mean global temperature range from only 1.0 to 1.8 °C. This is consistent with findings by Parry et al. (1999). In addition, the declines in world crop production reported here occur even though this study's modeling framework simulates more adaptive behaviors (including the exploitation of land newly suitable for agriculture at high latitudes) than Parry et al.'s modeling framework. On the other hand, Parry et al.'s results also include the beneficial effects of CO_2 fertilization. Climate change in this analysis pertains only to changes in temperature and precipitation patterns. Also the impacts on world food consumption and economic welfare reported here are uncertain. Results in this paper also confirm that costs and benefits of climate change are not equally distributed around the world, but that confidence in impacts with respect to variable projections of climate depends on economic conditions.

Results in this paper also confirm that CO_2 fertilization is likely to provide economic benefits and that the benefits are generally larger in regions where agriculture is a relatively large component of the total economy. CO_2 fertilization may generate economic losses, however, in regions that rely heavily on agricultural exports as a source of income. Finally, as might be expected, results in this and an earlier paper indicate that the economic benefits of CO_2 fertilization for the world as a whole are smaller when the atmospheric concentration of CO_2 is lower. The benefits reported here for a 150-ppmv increase in atmospheric CO_2 (a 0.48% increase in 1990 world per-capita welfare) are smaller than for a 225-ppmv increase in atmospheric CO_2 (e.g., a 0.67% increase in 1990 world per-capita welfare) reported in Darwin and Kennedy (2000).

Much research still needs to be done. First, the analysis is based on results from only one model with limited capabilities. The limitations tend to generate biased estimates. Results presented here, for example, probably underestimate the potential agricultural damages of climate change because they exclude potential damages of sea level rise and extreme events, such as droughts and floods. Also, because of its high level of aggregation, the Rest-of-World region in FARM's economic model provides upwardly biased estimates of the economic impacts of climate change when mean global temperature increases by 2.8 to 5.2 °C (Darwin, 1999). Hence, additional research awaits improved methods for estimating economic impacts of greenhouse gas emissions. This would include expanding the types of impacts considered, increasing the geographic resolution of the model, and introducing more complex responses by individuals and institutions. Also, the impacts of climate change and CO_2 fertilization should be simulated simultaneously.

Second, links between variable projections of climate and economic activity are not fully established in this paper. My methods for analyzing uncertainty due to variable projections in climate do explicitly link increases in mean global temperature with their average economic impacts. Deviations of economic impacts from trends are only assumed to be related to variations in projections of regional temperature and precipitation. This is a sound assumption because the design of the analysis controls for changes in other variables. Additional research would statistically estimate the relationships between deviations from mean economic impacts and deviations from mean temperature and precipitation, at both regional and global scales. This would help locate regions where agricultural production and economic welfare are either particularly sensitive and/or uncertain with respect to climate change. Such analyses need to be conducted with state-of-the-art projections of climate change.

Third, alternative projections of economic conditions in this analysis are decoupled from greenhouse gas emissions, their agronomic and other impacts, and any subsequent economic feedback. This limits the ability to conduct comprehensive analyses of the uncertainty surrounding variable projections of economic activity. A specific agricultural limitation along this line is that total factor productivity of crops is presumed to be independent of climate change and CO_2 fertilization. This is due in part because the extent to which climate change or CO_2 fertilization have enhanced or hindered increases in total factor productivity of crops in the past is not known. Research on this topic would enable more reliable projections of total factor productivity. Research pertaining to potential agronomic advances related to greenhouse gas emissions also is needed. Advances specific to climate change include increasing crop tolerance to heat or drought and shortening growing seasons. An advance related to CO_2 fertilization is enhancing the ability of crops to concentrate CO_2 in their leaves above ambient levels. The benefits of the former are straightforward – they would enable crop production to continue in areas that otherwise might become unsuitable. Some of the benefits of the latter are less obvious. In addition to increasing agricultural productivity, the development of crops with enhanced abilities to concentrate CO_2 would reduce the economic benefits of CO_2 fertilization because crop yields would not increase as much in the future as they do now under higher concentrations of atmospheric CO_2. This in turn would reduce the opportunity cost of reducing concentrations of atmospheric CO_2. Last but not least, future research would evaluate how public policy on agronomic research as well as on economic growth and development in general would affect economic impacts of greenhouse gas emissions.

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